REFERENCE-DISPLAY SYSTEM FOR THE INTEGRATION OF CT SCANNING AND THE OPERATING MICROSCOPE

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Abstract

With the introduction of computed tomography (CT) scanning in 1972, advancements in diagnostic radiology and related disciplines have soared. This rapid growth has led not only to more advanced diagnostic technologies, but also to more advanced CT applications. A reference - display system has been developed to superimpose reconstructed CT images on the operative field, providing the surgeon with information that permits greater precision during operative procedures than presently possible.

The CT images, reconstructed from conventional transverse oriented CT scans to match the surgical perspective, are displayed on a miniature CRT and superimposed at the focal plane of the operating microscope by a beam splitting assembly. The spatial registration of the CT data, operating microscope and patient are accomplished by the adaptation of an ultrasonic digitizer, incorporating an array of three small spark gaps mounted on the microscope and used in conjunction with an array of ceiling mounted microphones. Glass fiducials, temporarily attached to the patient allow the CT scans, patient and microscope to be optically referenced.

The total reference system error was found to be approximately one millimeter.

ACKNOWLEDGEMENTS

So many people have been involved directly and indirectly with this project that it is difficult to thank everyone, but I will try.

I would like to express my sincere thanks to: John Strohbehn for his wisdom and confidence - maybe now I'll get out of the "digitizer coordinate system!", David Roberts for his creativity and engineering insight which never ceases to amaze me, and Eric Hansen for his advice and exceptional teaching ability.

Thanks are also due Wendy McDowell, Roger Howes and Bill Murray for their guidance and friendship, and the staff at the Mary Hitchcock Hospital.

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J.F.H.
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Chapter 1 - Introduction

With the introduction of computed tomography (CT) scanning in 1972, advancements in diagnostic radiology and related disciplines have soared [20]. This rapid growth has led not only to more advanced diagnostic technologies, but also to more advanced CT applications. Through the use of computers, high resolution three-dimensional visualization of previously unseen structures is now available [20].

Integration of this technology with operative neurosurgery remains in its infancy. Stereotactic surgery utilizes a fixed reference frame attached to the patient's head to place EEG electrodes, take tissue biopsies, etc., with better than 1 millimeter precision. This technique has the capability to incorporate the available computer technology with the operating room environment and many neurosurgical procedures. Concurrent with these developments, the field of neurosurgery in general has evolved to a higher art through the development of the operating microscope. We propose to integrate CT and computer technology with stereotactic principles and the operating microscope to develop a computer-based optical system for use during microneurosurgical procedures.

At present, a neurosurgeon's ability to perform intracranial procedures for tumor, vascular disease or functional disorder is dependent upon his mental integration

of the visualized operative field with his knowledge of neuro-anatomy and the available radiologic studies such as CT scans. Available technology could greatly improve that mental process and achieve a far superior degree of operative precision and safety.

Conventional CT scans are oriented transversely to the body axis and as the operative approach is rarely along the axis of conventional scanning, the ability to reconstruct a CT scan to match the surgical perspective is highly appealing. The major objective of this project is to develop a system that will superimpose reconstructed CT images over the field of view of the operating microscope. The neurosurgeon would then see, for example, the outline of a tumor superimposed on the operative field.

There are a number of advantages of this reconstruction/projection system:

1) There would be no dependence on the surgeon's mental reorientation of CT scan information.

2) The information would be displayed such that it would not interfere with the neurosurgeon's procedure or require the reading of x-rays off a light screen some distance away.

3) A computer-based anatomical atlas could be developed that would superimpose on the operative field important but otherwise unseen structures, such as normal neuronal pathways and nuclei and major vascular structures [2].

4) The neurosurgeon could use the superimposed image as a map accurately guiding operative procedures with greater precision than presently possible.

1.1 Recent Research

Recent work in CT scanning and reconstruction has been well established and involves primarily image processing software and computer graphics [1,3]. This project will require original application of presently developed techniques.

Adaptation of stereotactic technique to CT technology has been approached in a number of ways. One useful technique is that developed by Leksell at the Karolinska Institute in Stockholm, utilizing an adapted metal frame fixed to the patient's head at the time of scanning [26,27], (e.g. Figure 1.1). Stereotactic coordinates, relating the target position of CT demonstrated pathology to the stereotactic instrument, are generated directly from the scans and the patient is then transported to the operating room [27,30]. Other techniques are adequate but often more cumbersome [4-7,9,12-17,21,22,28,29,31-37,39-42,48]. All of these enable stereotactic procedures generally characterized by "blind" insertion of needle-like instruments through small openings utilizing previously obtained CT-determined landmarks. This has been a vital development and a foundation for this project. They have not generally been

Figure 1.1 - Stereotactic Frame

amenable to "open" procedures such as craniotomy for tumor or vascular disease and, as previously noted, do not allow access to CT data after selection of a target. The CT information utilized is limited to the coordinates of a point. All instruments select a target and set the instrument accordingly; the proposed system, operating in reverse, allows free positioning of the microscope with subsequent stereotactic "positioning" of the CT data.

The operating microscope has been incorporated into CT stereotactic work by Kelly at the State University of New York at Buffalo [23,24]. This development has also employed surgical laser instrumentation and shown the feasibility of

achieving a synthesis of technologies and the prospects of refining neurosurgical operative technique. His technique of linking the operating microscope and the stereotactic reference system requires utilization of a large stereotactic frame. The proposed system will eliminate the encumbrance of such a frame and in doing so permit a potentially wide-spread applicability to general neurosurgery. Kelly's system has not employed a projection system as proposed in this project.

1.2 Problem Statement

The goals of this project are to design a system that will reconstruct CT images from diagnostic CT scans and superimpose the reconstructed image on the magnified field of the operating microscope.

The overall project can be divided into four parts.

1) The data from the CT scanner/computer must be transferred from the computer's memory into another form that can be manipulated in the operating room.

2) Computer algorithms and programs must be developed to calculate the new reconstructed CT image based on the position of the operating microscope with respect to the patient's neuro-anatomy, as presented in the CT scans.

3) A system must be developed to display the new reconstructed CT image within the operating microscope.

4) The operating microscope must be linked or referenced to the coordinate system of the CT scan and the patient.

Our initial design will be to reconstruct only certain CT boundaries or contours (such as the outline of a brain tumor) and if this technique proves useful, future developments will reconstruct grey scale CT information.

1.3 Thesis Objectives

The specific objectives of this thesis are to address the last two points of the Problem Statement and to construct the hardware necessary for displaying referenced CT scans within the operating microscope. In order to more clearly define the reference - display system, the reconstruction technique must be outlined. It has been determined that manipulation and reconstruction of CT images would be best handled by the Treatment Planning Computer (a Data General Eclipse S130 based system manufactured by General Electric) located in the Norris Cotton Cancer Center at the Mary Hitchcock Hospital, since this system has the capability to read the formatted CT scans stored on magnetic tape by the G.E. CT Scanner. Figure 1.2 shows a block diagram representing the overall system.

The objectives of this thesis are:

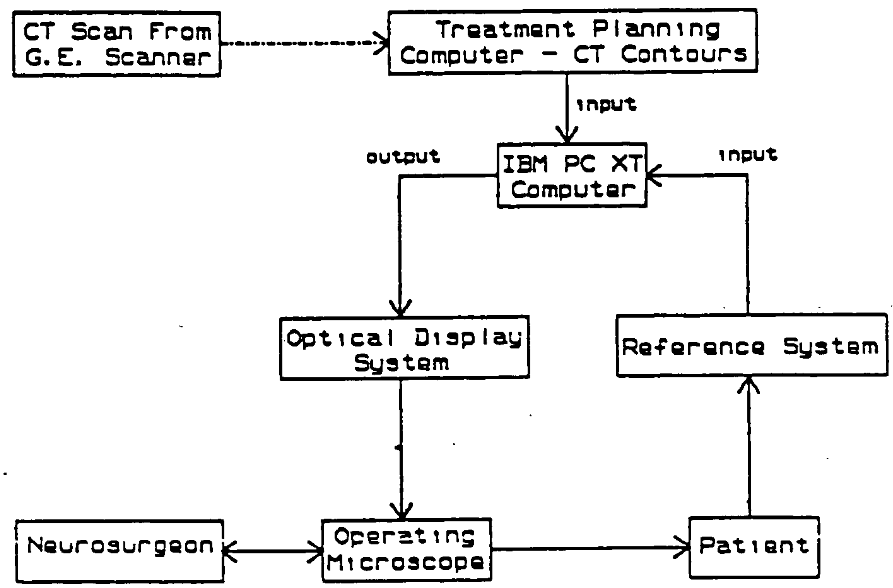


Figure 1.2 - System Block Diagram

1) to provide the Treatment Planning Computer with enough information concerning the position of the operating microscope with respect to the patient and CT scans to reconstruct the appropriate image;

2) to superimpose the reconstructed image onto the field of view of the operating microscope;

3) to design and build all the hardware necessary for the reference - display system and

4) to evaluate the system's performance.

1.3.1 Specifications

There is only one specification concerning the design of the reference - display system: the system should display a reconstructed CT image of the correct structural

anatomy within 1 millimeter (comparable to the stereotactic frame) or prove that constraints prevent this accuracy from being achieved.

1.3.2 General Constraints

This system must meet the constraints of the operating room environment and not impair or reduce the effectiveness of the operative procedure. The system must also be simple to use, allow modifications for new applications, and remain within budget constraints of $13,500. Specific constraints are indicated in each chapter.

1.4 Thesis Organization

This Thesis is divided into twelve chapters and seven appendices. In general, each chapter describes a different aspect of the project and includes specifications, constraints, alternatives and a description of the selected alternative. Chapter 2 describes the operating room environment and the constraints associated with neurosurgical procedures. Chapter 3 describes the optical display system and, more specifically, the choice of beam splitter and image display.

The remaining nine chapters address the problem of referencing the reconstructed CT image to the position of the operating microscope. Chapter 4 outlines proposed alternatives for the reference system. The selected

registration technique, an ultrasonic linkage, is discussed in Chapter 5. Chapter 6 explains the various coordinate systems and Chapter 7 describes the theoretical error analysis. Chapters 8 through 10 detail the specific hardware design of the spark gap multiplexer, reference system software, and mechanical designs of the spark gap holder and microphone mounts, respectively. The system evaluation and experimental results are described in Chapter 11, and Chapter 12 concludes the Thesis with an outline of future work and a future design.

The appendices include schematics, test statistics, software, mechanical designs, experimental results and a digitizer operator's manual.

Chapter 2 - Operating Room Environment

The operating room environment imposes three general constraints on any procedure:

1) physical constraints on the positioning and movement of equipment;

2) aseptic constraints on the cleanliness of equipment in the operating room and within the operative field;

3) safety constraints on electrical equipment used within 15 feet of the patient.

2.1 Physical Constraints

For the purpose of this project, the operating room can be broken down into six basic components that place restrictions on the positioning and movement of equipment: the patient, the surgeons, the scrub nurse and surgical instruments, the anesthesiologist and anesthetic equipment, the operating microscope, and the ceiling-mounted operating room lights. Each of these components are in different positions within the operating room depending on the surgical procedure. There are three neurosurgical operative setups depending on the type of surgical procedure and the craniotomy site. Procedures involving operations with the patient in the sitting or supine positions for frontal or right temporal craniotomies are set up as shown in Figure 2.1 and 2.2. Procedures involving left temporal

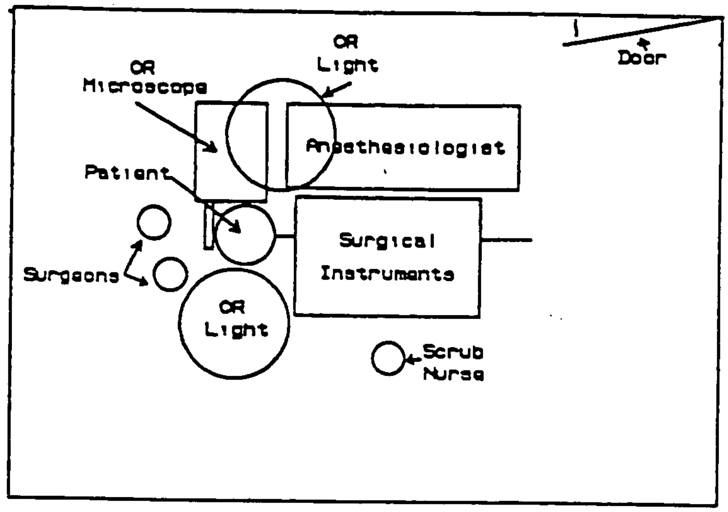


Figure 2.1
Sitting/Supine Right Temporal Craniotomy

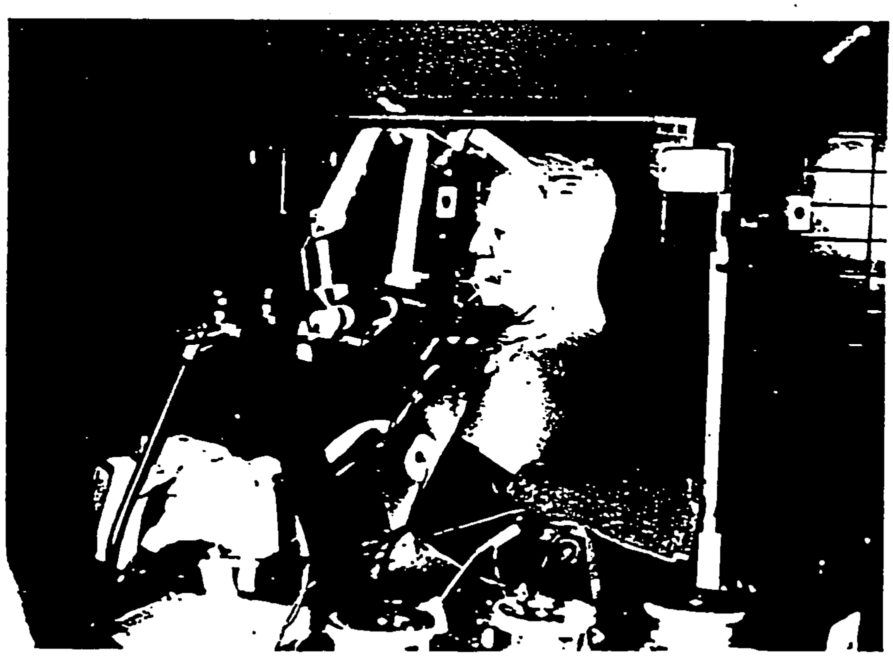


Figure 2.2 - Sitting Position

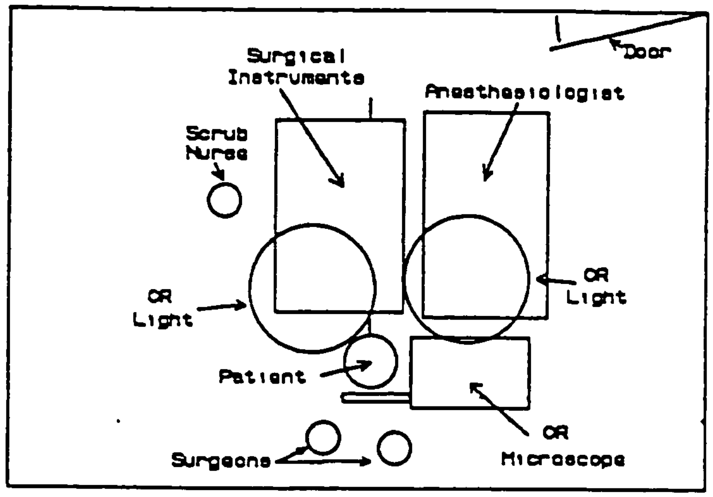


Figure 2.3

Supine Left Temporal Craniotomy

craniotomies are set up as shown in Figure 2.3. These setups allow sterile draping such that the anesthesiologist has proper access to the patient. The operating lights are attached to ceiling-mounted light tracks, between which is an air output vent. See Figure 2.4.

2.2 Aseptic Constraints

Every instrument, person, and piece of equipment in the operating room must be either clean or sterile. All items must be clean - i.e. free of dirt, oils and other contaminants conducive to the growth of potentially infective organisms. Equipment brought into the operating room must withstand a general cleaning procedure. Items directly and indirectly involved with the operative field

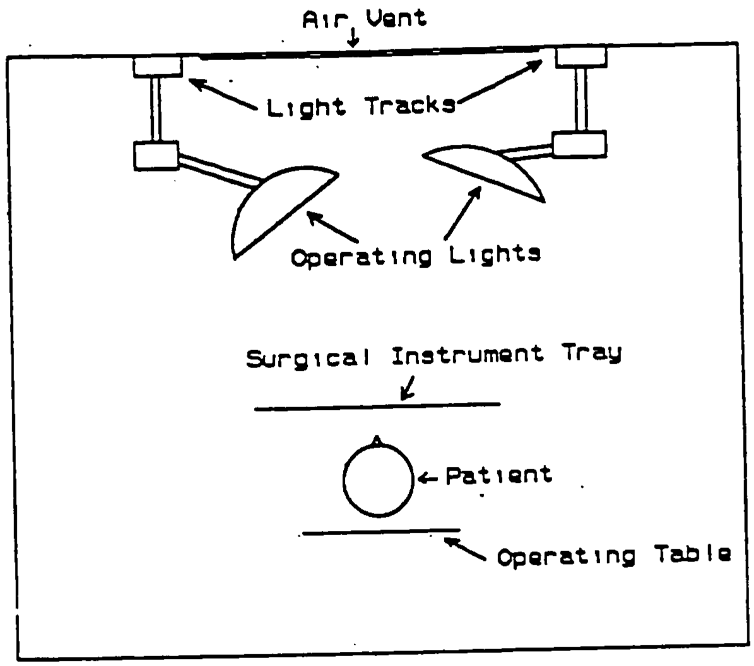


Figure 2.4 - Operating Lights

must be sterile, i.e. not only clean, but ideally free of all microbial organisms. This includes anything touching the operative site.

Not all equipment within the sterile field must itself be sterile, but it must be covered with a sterile barrier. Examples of items that must be sterile or contained within sterile drapes include surgical instruments, the surgeon's hands, arms and front body and anything hanging over the operative field that has the potential to come in contact with sterile areas.

There are two different sterilization procedures depending on the material to be sterilized. Stainless steel and other metals that will not oxidize if exposed to steam or aqueous solutions must withstand a temperature of 243°F

for 20 minutes. Teflon and plastics must undergo ethylene oxide gas sterilization at 130°F for 24 hours [44].

2.3 Safety Constraints

Any electrical equipment used within 15 feet of the patient must meet the National Fire Protection Association (NFPA) safety standards [44]. These standards include: proper three conductor a-c power line cord with hospital/operating room grade plug, properly connected grounding pin with no more than 100 microamps of leakage current, and a resistance between the grounding pin and chassis of less than 0.2 ohms.

The most difficult of the standards to maintain is the leakage current limit. The leakage current can be reduced by powering the equipment through an isolation transformer.

2.4 Operating Microscope

The operating microscope used for neurosurgical procedures at the Mary Hitchcock Hospital is a Zeiss OPMI-1H with a Contraves floor stand, (Figure 2.5). The microscope is used to magnify the operative field approximately five to thirty times. The optics incorporate either a 250 or 300 millimeter objective lens with five parafocal lens settings, allowing five magnifications with little focal length

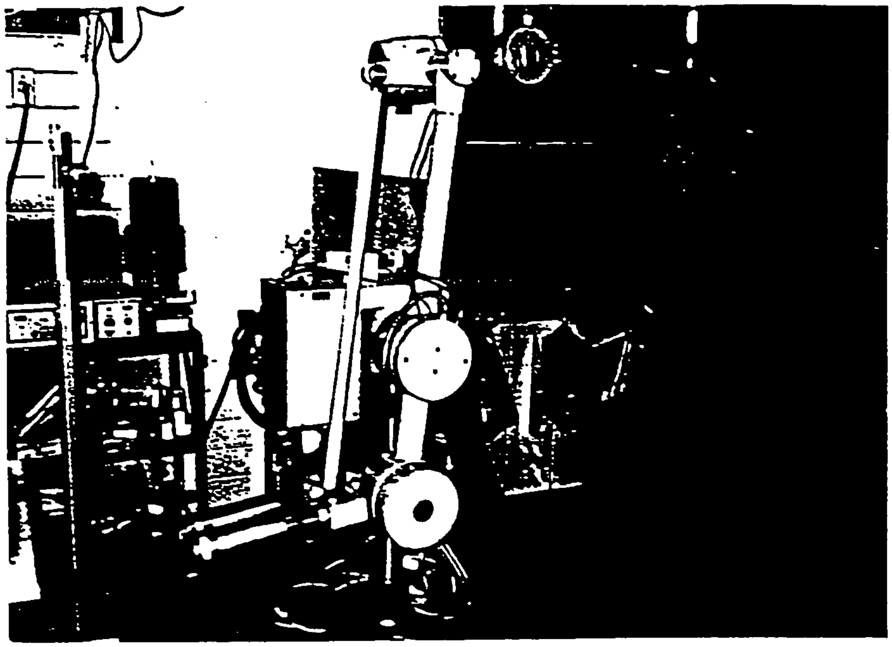


Figure 2.5 - Zeiss Operating Microscope

adjustment. The range of the magnified operative field is 9.5 to 1.45 centimeters in diameter. See Table 2.1 below.

Table 2.1 - Optical Specifications

Magnification Setting	Magnification [19]	Field Diameter in cm.	Depth of Field in mm.
2.5	13.0x	1.45	2
1.6	8.3x	2.30	4
1.0	5.2x	3.70	7
0.6	3.1x	6.10	19
0.4	2.1x	9.50	>19

The internal ocular-to-objective optics are all focused to infinity, allowing for the addition of other optical equipment, i.e. irises and beam splitters, without changing the optical characteristics of the microscope. The

microscope also incorporates a through-the-objective illumination system with two degrees of brightness.

The microscope mount is a six jointed, six degree of freedom Contraves floor stand with pistol grip, and a foot pedal or mouth switch activated servo-mechanisms to lock the microscope in place. When the microscope is properly counter-balanced, the surgeon can use the mouth switch to release and reposition the "floating" microscope.

The microscope is also equipped with a beam splitting device for the attachment of a stereo-observation tube and either a color video camera or a 35 millimeter camera.

To insure proper aseptic technique, specially designed sterile transparent plastic bags are draped over the microscope and most of the floor stand, (Figure 2.6).

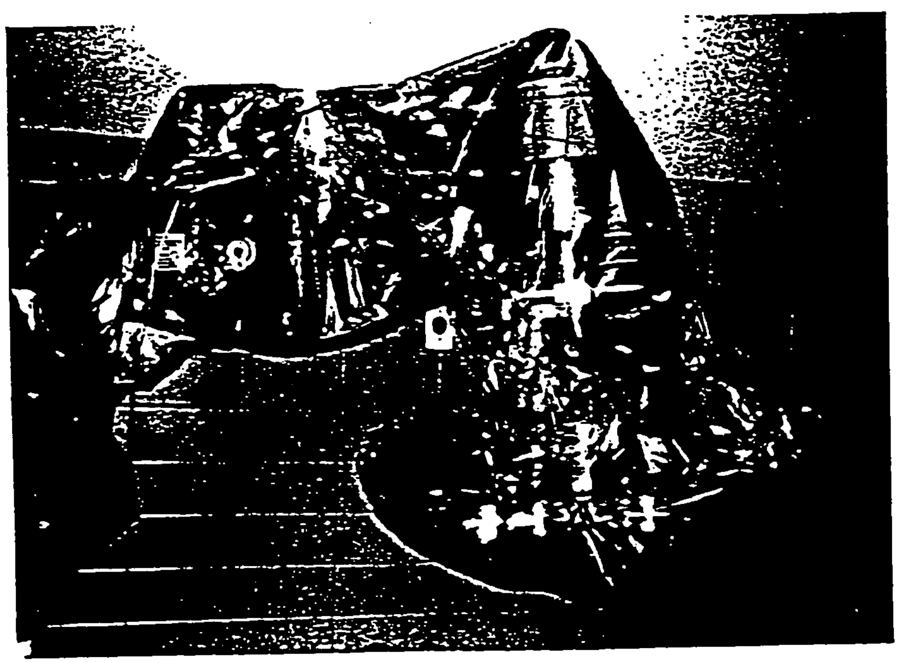


Figure 2.6 - Draped Operating Microscope

Chapter 3 - Optical Display System

This chapter describes the constraints and alternatives of the optical display system and the video connections necessary for displaying the reconstructed CT image.

3.1 Constraints

To display a reconstructed CT image at the focal plane of the operating microscope, a beam splitting device is introduced into the optical path of the microscope. This device can be used to superimpose or "add" two images. See Figure 3.1. The constraints on the beam splitting assembly are:

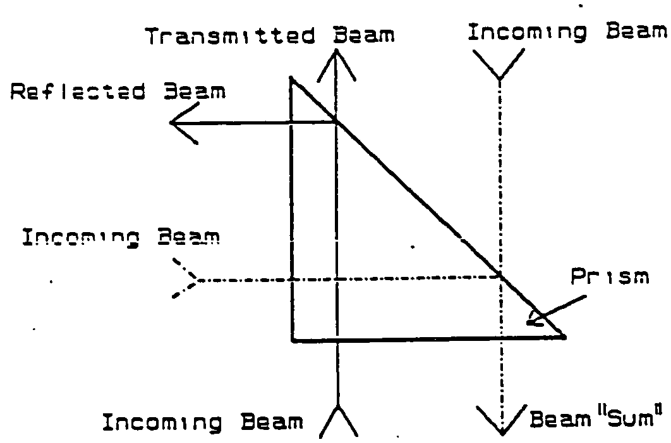


Figure 3.1 - Beam Splitter

1) The beam splitter must have a reflection - transmission coefficient ratio such that superimposed images are not "washed out" by the illuminated operative field.

2) The prism optics must not introduce any visually disturbing glare or aberrations.

3) The additional optical path length must be less than 25 centimeters to maintain an acceptable surgeon eye-to-hand distance of less than 45 centimeters.

4) The weight of the beam splitter must be less than 4 kilograms and the size must be less than 10x20x10 centimeters to remain within limits for balancing the microscope and not interfere with the surgical procedure.

The image source of the reconstructed CT scan must be introduced into the beam splitting assembly in order to be superimposed on the focal plane of the microscope. Since CT scans are computer generated images displayed on a video screen (unlike conventional X-rays that are produced on translucent, plastic X-ray film), this CRT (Cathode Ray Tube) image would provide an appropriate and convenient image source for the beam splitter. The constraints governing the image display are:

1) The display screen must be bright enough to effectively superimpose an image on the illuminated operative field.

2) The CRT must be easily mounted on the microscope, weighing less than 1 kilogram for proper balancing, and not interfere with the surgical procedure.

3) The CRT must possess enough resolution to display a crisp image.

3.2 Zeiss Drawing Tube

The alternatives for a beam splitting assembly are either to purchase a manufactured assembly, design our own, or combine the best features of both. Since Zeiss manufactures the microscope and assumes liability for its operation (any piece of non-Zeiss equipment attached to the microscope would void the Hospital's liability contract), manufactured assemblies are preferable and were investigated first. A beam splitting assembly manufactured by Zeiss is optically compatible with the OPMI-1H operating microscope. It is sold as a drawing tube to allow biological illustrators to superimpose their sketch pad on the magnified field for more accurate illustrations. The model that is optically compatible with the microscope is #474622. See Figure 3.2. It consists of a 50/50 binocular beam splitter (that will mount between the objective lens of the microscope and the observation tube/video camera beam splitter) and a projection tube approximately 20 centimeters long and 4 centimeters in diameter. There are two movable lenses in the tube; one is for focusing the superimposed

Figure 3.2 - Zeiss Drawing Tube

image and the other is for magnification. A prism at the end of the tube directs the drawing surface through the projection tube to the beam splitting prism. Since the OPMI-1H microscope is an older model, the drawing tube presently available was mechanically modified to fit the microscope. This modification, done by Fred Schleipman, involved reducing the size of the beam splitter housing by 1.27 centimeters on one side and replacing a thumbscrew with a recessed set screw. The drawing tube adds approximately 4 centimeters to the optical path length and, for a proper mechanical fit, a 2.5 centimeter spacer must be added to lift the beam splitter above the focusing knob.

3.3 CRT Display

There are many CRT's that will display composite video images from the Treatment Planning Computer, but few that will meet the constraints of size and weight. A screen size of 5 centimeters square or less is preferable. Most portable video cameras have electronic viewfinders consisting of miniature CRT displays which accept composite video inputs and would be compatible with the beam splitter. An electronic viewfinder (model #VF-1900) was purchased from J.V.C. that has a 38 millimeter diagonal black and white CRT and all the display driving electronics, accepts a standard composite video signal, weighs approximately 0.5 kilograms, is small enough to not interfere with any surgical procedure, has brightness and contrast control, and has very good image resolution. See Figure 3.3.

Several simple modifications were required to make the viewfinder compatible with the Zeiss beam splitter. BNC connectors were added for the video input signal and +12 volt dc power supply. The field lens and flexible rubber eye gasket were removed on the viewfinder and the mirror prism assembly was removed from the drawing tube to allow the plastic housing of the viewfinder to close around the end of the projection tube. To ensure a rigid fit, a hard rubber coupling was contact cemented to the projection tube and a small metal alignment pin was machined to fit the lens

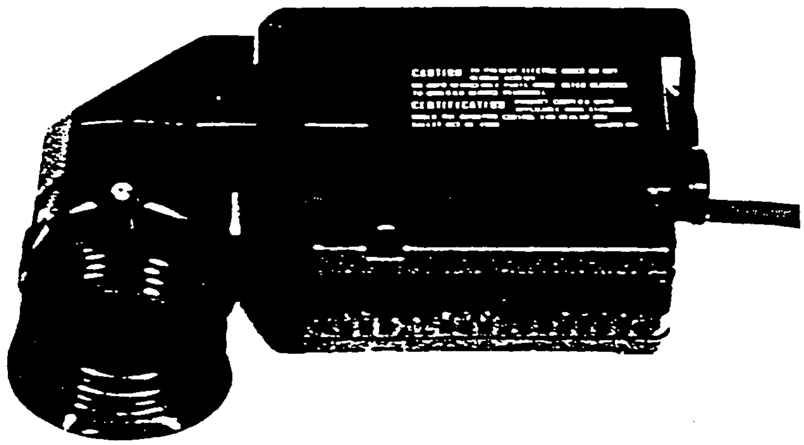


Figure 3.3 - Miniature CRT Display

guide, preventing twisting and drooping of the display while attached to the microscope. The angle of the display and drawing tube was chosen not to interfere with the surgeon's hands. See Figure 3.4. This type of attachment was made as an initial connection. Should the surgeon later find this cumbersome, or a more permanent structure becomes necessary (i.e. such that the projection tube be shortened or just the CRT itself be attached to the projection tube) this design can be easily modified. Figure 3.5 shows the attachment of the beam splitter - CRT assembly to the operating microscope.

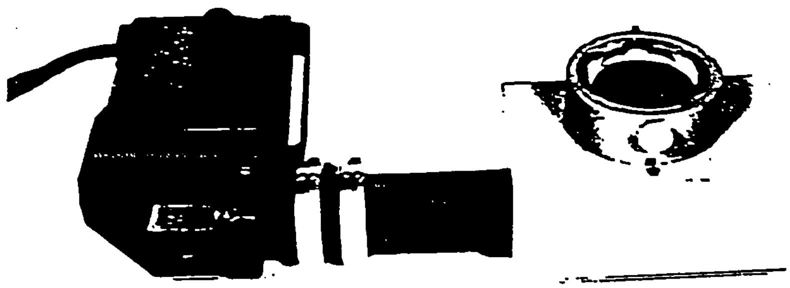


Figure 3.4 - Beam Splitter - CRT Assembly

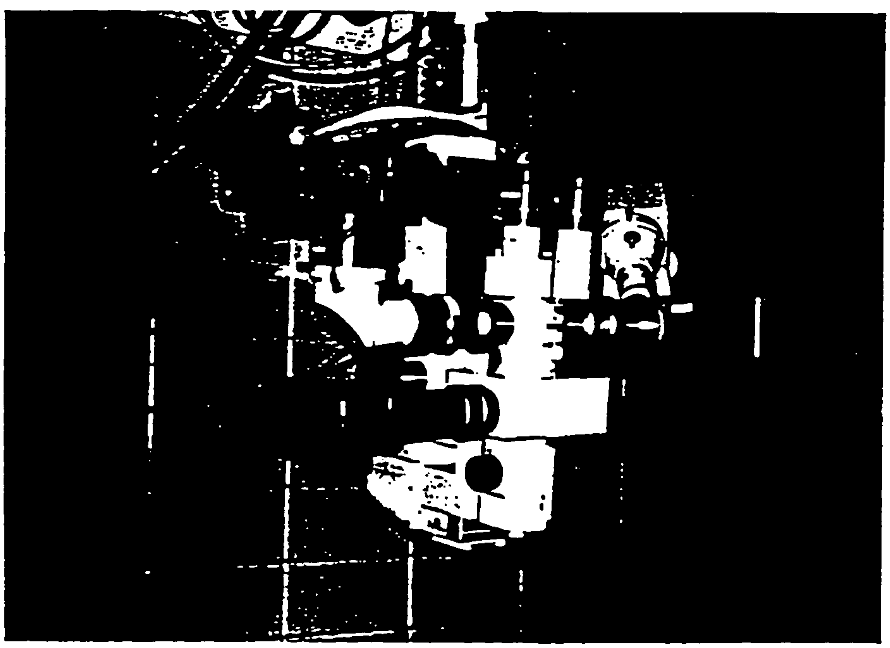


Figure 3.5 - Microscope - Display System

3.4 Interact TV Connections

The work station for the Treatment Planning Computer has a composite video signal output. The reconstructed CT image that can be displayed on the work station monitor must be displayed on the miniature CRT in the operating room. Therefore, a video connection is necessary. Since the work station is in the basement of the Hospital and the operating suite is on the second floor, a simple, quick video connection was unlikely. The alternatives for making this connection were to string a video cable from the work station to the operating room or to use some existing connections. Since the Hospital has an audio-visual system, Interact TV, that can provide this type of connection, the last alternative is viable and was selected. Radiation Therapy also has audio-visual lines connecting various rooms in the department, including the computer room. Upon consulting Ray Culig at Interact TV, a patch design was made. It involved connecting the work station output to the Radiation Therapy network, which terminates in the Hospital sub-basement, and connecting the sub-basement signal to the Interact TV lines that run up to the fifth floor where a video patch connects the line to the Interact Control Room on the first floor. From there the signal is patched to the operating suite - operating room 10 (which conveniently is used for neurosurgery). See Figure 3.6. These video lines

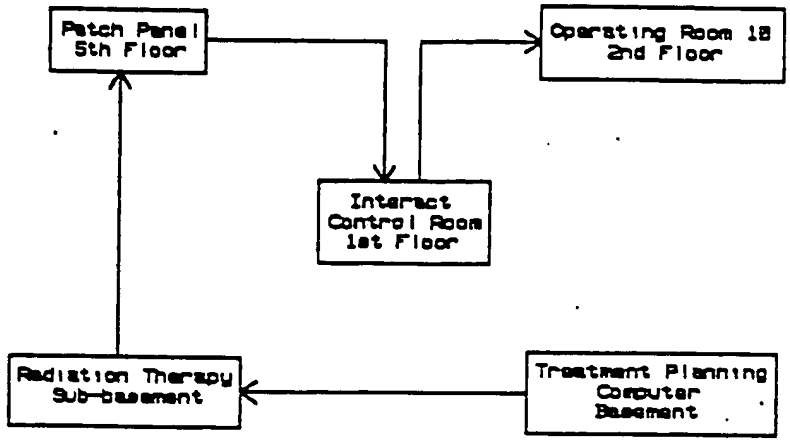


Figure 3.6 - Interact TV Video Connections

were tested and there is no need for signal amplification or frequency compensation (high end boost). This dedicated video line has been rented until March, 1985.

One other modification was required on the miniature CRT. The work station was manufactured in Europe and consequently has a 50 Hz video display scan rate which is incompatible with the miniature CRT. The horizontal hold on the CRT did not have enough range to display a stable image, so the horizontal hold potentiometer and a resistor were replaced to allow enough range for a stable image. See Appendix A for modified schematics.

Chapter 4 - Reference System

This chapter describes constraints (4.1) and alternatives (4.2) for the design of a reference technique that will coordinate the registration of the reconstructed CT image with the physical anatomy as observed through the operating microscope. The specific requirement of such a reference system is that the information from the diagnostic CT scans be reconstructed to match the focal plane from the operating microscope and superimposed in the microscope within 1 millimeter of the correct anatomy. Therefore, enough information must be available to calculate the equation of the focal plane and its orientation with respect to the microscope.

4.1 Constraints

The constraints on the reference system are:

1) It must meet the physical, aseptic and safety constraints of the operating room.

2) It must allow clear visualization of the magnified operative field and, if needed, only require a minimum of alterations to the microscope.

4.2 Alternatives

4.2.1 Stereotactic Linkage

Since the stereotactic frame (described in Chapter 1) determines its own coordinate system, mechanically linking the microscope to the frame after the patient has been CT scanned would provide a direct technique for determining the position of the focal plane. Such a linkage is shown in Figures 4.1 and 4.2. Unfortunately, the stereotactic frame not only limits the positioning of the microscope, but it also restricts the operative field and craniotomy site, making this system applicable to few procedures. This design was, therefore, not considered.

4.2.2 Cranial Linkage

To avoid the problem of the stereotactic linkage, a mechanical connection could be made from a small plate rigidly attached to the patient's skull (away from the craniotomy site) to the microscope. This cranial linkage could include the minimum number of joints (monitored by transducers) to allow the microscope enough degrees of freedom for proper motion. A coordinate system could be established by CT scanning the patient with the skull plate in place, detecting at least three known points on the CT

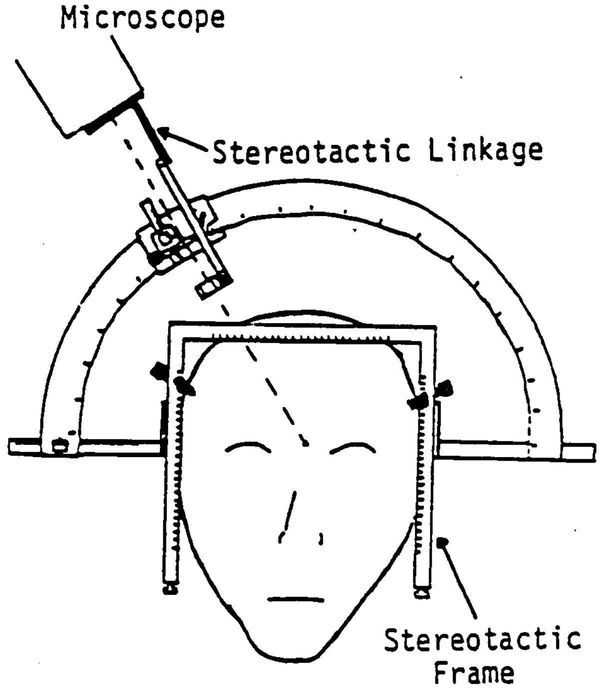


Figure 4.1

Stereotactic Linkage - Front View

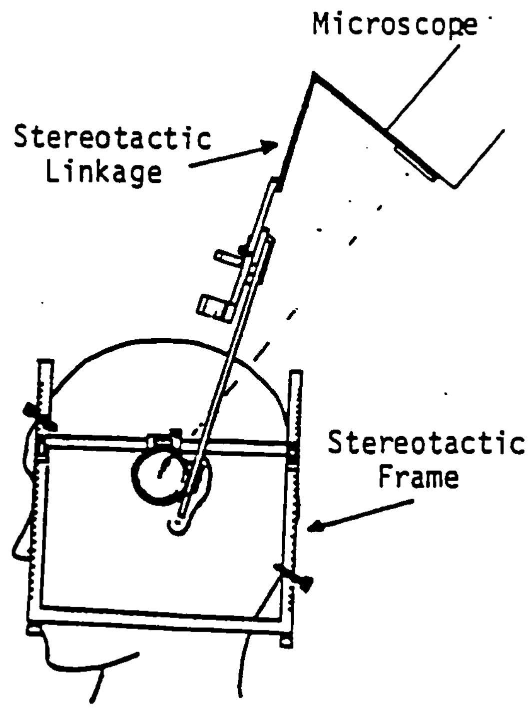


Figure 4.2

Stereotactic Linkage - Side View

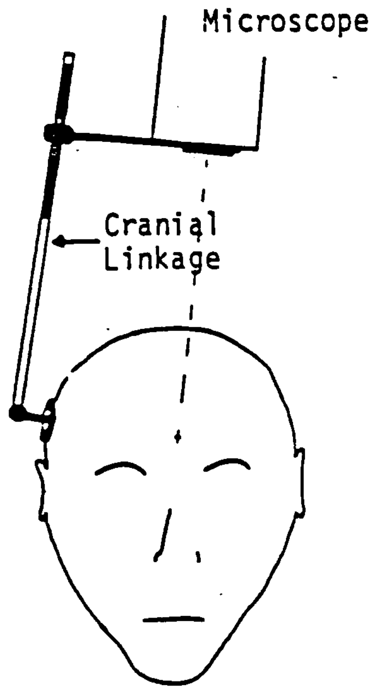


Figure 4.3
Cranial Linkage

scans. The microscope's position could then be monitored with respect to this coordinate system. See Figure 4.3.

4.2.3 Microscope Stand Redesign

The microscope stand could be redesigned to translate and rotate with respect to a fixed coordinate system. The coordinates of the focal point and the equation of the focal plane could be determined directly from the scales on the microscope stand or by computer-monitored transducers.

In order to relate the equation of the focal plane in a fixed coordinate system to the CT scans, the relative location of the CT coordinate system must be known. This can be achieved by determining the transformation matrix (see section 4.2.4.2) to convert coordinates in the fixed coordinate system to coordinates in the CT coordinate system. Transformation matrices can be defined by determining three linear translation constants and three rotational angles - a total of six pieces of information. Since angular information cannot be directly derived from the relative positions of the fixed and CT coordinate systems, the coordinates of at least three non-collinear points (nine pieces of information), common to both coordinate systems, must be determined. The transformation matrix can then be calculated with six of the nine coordinates. However, using only two of the three points will not uniquely relate the positions of the coordinate systems about the line through the two points.

The common points can be three CT-detectable markers or fiducials placed on the patient's head before CT scanning. The fiducials will appear in the CT scans and can be assigned coordinates by the scanning computer based on the CT coordinate system. When the patient is brought into the operating room the microscope can be focused on each of the fiducials and their coordinates determined in the fixed coordinate system. Once the transformation matrix is

calculated the equation of the focal plane can be determined in CT coordinates.

This alternative might be the best design once the CT scan - operating microscope technique has been proven useful. It would be too time consuming and expensive to consider at this point.

4.2.4 Microscope Position Tracking

By mounting position transducers on the six joints of the microscope stand (design I) or connecting the microscope with a multiple joint linkage to a fixed point with respect to the patient (design II), the microscope's position could be monitored with respect to a fixed coordinate system. Relating the fixed coordinate system of the microscope to the CT scans would be accomplished as described in section 4.2.3 above. This design would allow almost all procedures to be carried out normally. There would be no mechanical connection between the patient and the microscope to restrict the surgeon's procedure, and the microscope could be repositioned anywhere once a fixed coordinate system has been defined. The angular sensitivity required of the transducers for a less than 1 millimeter accuracy at the focal plane might require expensive transducers and sophisticated driving electronics. Also, applying the transducers would involve mechanical modifications of the microscope stand,.which was to be avoided if possible.

Since this design appeared practical, it was investigated further.

4.2.4.1 Theoretical Linkage Analysis

In theory, at least six pieces of information must be known about a rigid body (microscope/focal plane) to locate it precisely and without redundancy in a fixed coordinate space, see Figure 4.4. Therefore, any position locating technique must determine or monitor six degrees of freedom [43].

From the mobility formula (Kutzbach criteria) for spatial mechanisms (used commonly for closed kinematic chains, but which can also give degree of freedom information for open chains):

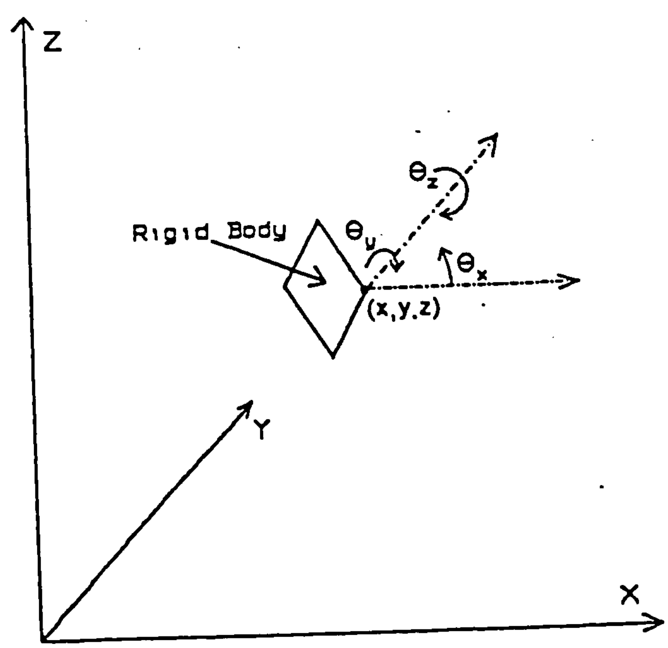


Figure 4.4 - Rigid Body Analysis

$$m = 6(n-1) - 5j_1 - 4j_2 - 3j_3 - 2j_4 - j_5$$

where m = # of degrees of freedom, n = # of links (rigid connections between joints) and j_1 to j_5 = # of joints with 1 to 5 degrees of freedom [42].

Six degrees of freedom are required, so $m = 6$, and since the basic single-degree-of-freedom, revolute joint is the most common and easily monitored by transducers, j_2 to $j_5 = 0$ and $j_1 = 6$. To determine the number of required links, n:

$$6 = 6(n-1) - 5(6),\ n = 7 \text{ links.}$$

See Figure 4.5.

4.2.4.2 Coordinate System Transformation

Transformation matrices are used to transform coordinates from one coordinate system to another. The position of the focal plane can be transformed into a fixed coordinate system by knowing the appropriate translations and rotations. Rotations can be characterized by a 3x3 matrix, indicating the axis of rotation, and a vector of the initial coordinates (x,y,z) [25]. See Figure 4.6.

Note: All rotations are counter-clockwise about the rotational axis while looking toward the origin.

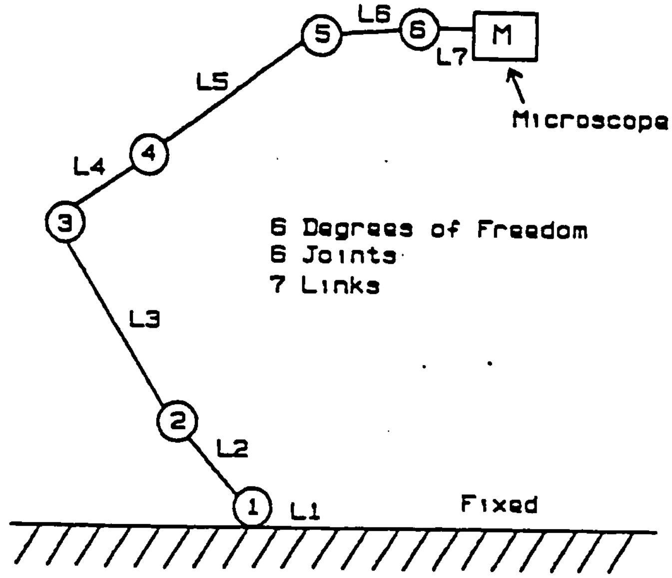


Figure 4.5 - Links - Joints

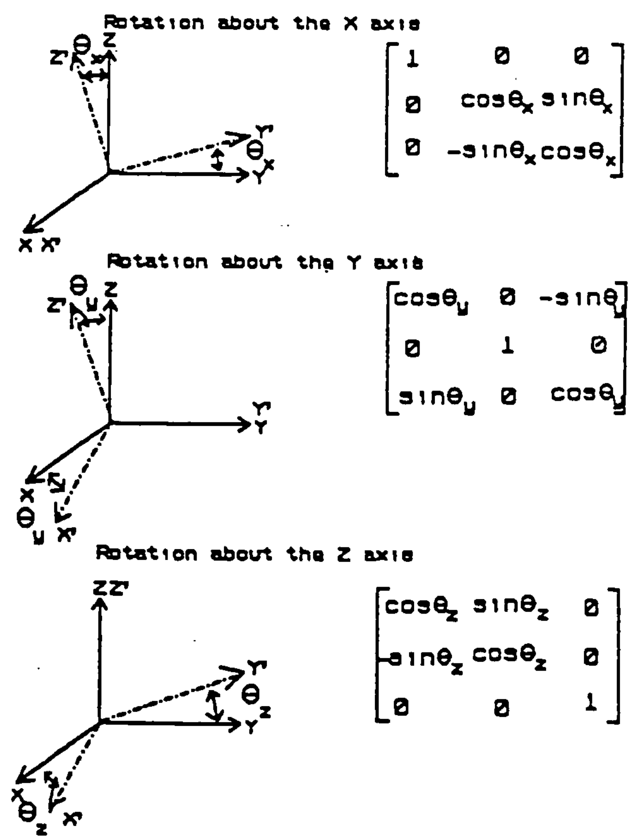


Figure 4.6 - Rotation Matrices

Multiplying the coordinates of a point in one coordinate system represented by a 1x3 column vector by a rotational matrix produces the coordinates of the point in a rotated coordinate system. Translations can be represented by a 4x4 matrix, where T_x, T_y and T_z are the magnitudes of the vectors along the x, y, and z axes, as shown below.

$$\begin{matrix} 1 & 0 & 0 & 0 \\ T_x & 1 & 0 & 0 \\ T_y & 0 & 1 & 0 \\ T_z & 0 & 0 & 1 \end{matrix}$$

Combining the two matrices yields a 4x4 matrix with the general form:

$$\begin{matrix} 1 & 0 & 0 & 0 \\ T_x & R_{11} & R_{12} & R_{13} \\ T_y & R_{21} & R_{22} & R_{23} \\ T_z & R_{31} & R_{32} & R_{33} \end{matrix}$$

T_x, T_y, and T_z is the translation vector along the x, y, and z axes respectively, while R is the rotational matrix. Written in this form, the translation takes place before the rotation [38]. Point(s) in one coordinate system can be transformed into another by multiplying the appropriate transformation matrices together. Six degrees of freedom requires six transformation matrices. Since matrix multiplication is not commutative, the multiplicative order of the transformation matrices is important.

4.2.4.3 Angular Measurement Alternatives

Both designs I and II depend on the accurate measurement of rotational angles. These angles can be measured electronically (providing a more precise processor-usable input) by using position transducers that convert a mechanical displacement into an electrical signal. Position transducers can give two types of output: analog and digital. Since the position of the microscope and the patient's head will be inputs to a digital computer the latter output is preferred.

Transducers presenting digital output for an angular displacement are called shaft encoders, and their output sensitivity (resolution) is measured in numbers of bits (angular fraction of 360°). There are two different kinds of shaft encoders: incremental and absolute. Incremental encoders give a pulse output such that by counting the number of pulses, the relative angular displacement can be found with respect to a user-defined zero value. Absolute encoders have a fixed binary output for each position of the shaft. Absolute encoders are preferred for this application since the electrical signal can be directly sent to a processor without pulse-counting electronics. Table 4.1 gives price ranges for various resolutions (# of bits).

Table 4.1 - Absolute Shaft Encoders

Resolution	Price Range
9 bits	\$400. - \$2500.
10 bits	\$400. - \$3000.
11 bits	\$2300. - \$3000.
12 bits	\$2300. - \$3000.
13 bits	\$2400. - \$3200.
14 bits	\$3200. - \$4000.

The most accurate analog output transducers are rotary variable differential transformers (RVDT). The accuracy of RVDT's is measured in percent nonlinearity - how well the voltage output versus displacement curve conforms to a linear relationship. This percentage increases with an increase in angular range. Table 4.2 shows the prices for various resolutions (converting percent nonlinearity to angular error in degrees) for Pickering RVDT's.

Table 4.2 - Pickering RVDT's

RVDT Model #	Range	Resolution	Price
23501	0-40°	±0.100°	\$148.85
	0-55°	±0.275°	
	0-65°	±0.650°	
	0-70°	±0.875°	
23511	0-10°	±0.025°	\$210.45
	0-40°	±0.120°	
	0-70°	±0.525°	
23300	0-10°	±0.010°	\$247.95
	0-40°	±0.100°	
	0-70°	±0.875°	
23380	0-10°	±0.005°	\$277.20
	0-40°	±0.060°	
	0-70°	±0.700°	

4.2.4.4 Microscope Stand Analysis

In order to estimate the accuracy and costs associated with tracking the position of the microscope, the microscope stand design was further analyzed. Figure 4.7 represents the microscope stand. The links were measured as accurately as possible (± 5 millimeters) and a transformation matrix was determined for each link-joint combination. The starting point vector provides the coordinates of the focal point with respect to an assigned Cartesian coordinate space whose origin is at joint 1. The angular range for each joint is indicated. See Figure 4.8.

A computer program was written to evaluate the transformation matrices and determine the tolerable rotational error for each joint, given the maximum focal

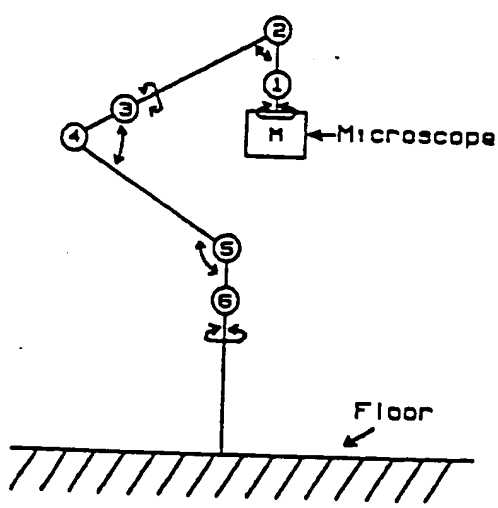


Figure 4.7 - Microscope Stand Model

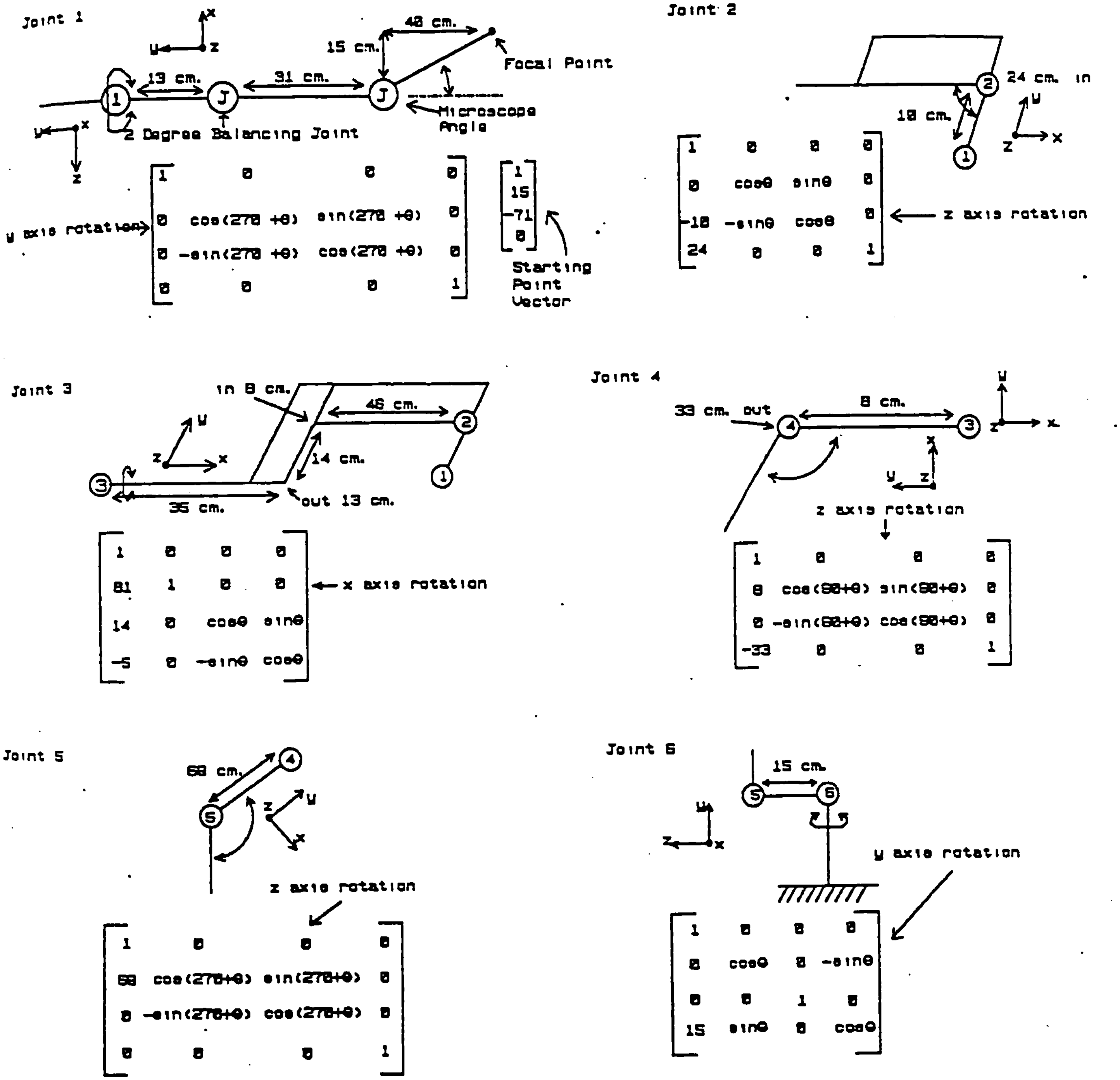


Figure 4.8 - Microscope Stand Joints

point displacement error of 1 millimeter. Table 4.3 below shows the rotational error in degrees, the number of parts of a circle (fraction of 360°) and the number of bits of resolution required for each joint.

Table 4.3 - Rotational Error

Joint #	Rotational Error	# Parts	# Bits
1	$\pm 0.392^{\circ}$	920	10
2	$\pm 0.081^{\circ}$	4445	13
3	$\pm 0.070^{\circ}$	5145	13
4	$\pm 0.054^{\circ}$	6670	13
5	$\pm 0.057^{\circ}$	6320	13
6	$\pm 0.037^{\circ}$	9730	14

The minimum referencing cost for the microscope stand linkage using shaft encoders is approximately $13,200 and using RVDT's, approximately $1,500. Analog-to-digital conversion circuitry would have to be built for the RVDT's, so the cost involved would be greater, but less than that for shaft encoders. This evaluation was based on the assumption that the total system error is due to angular microscope error and that errors in other parts of the display - reference system were zero. The actual design must be much more accurate.

4.2.5 Ultrasonic Linkage

Another technique for locating the microscope/focal plane would be to use ultrasonic principles to determine the distances between the microscope and fixed ultrasonic transducers. This would require a transmitting - receiving

network to send, receive and interpret the ultrasound. Science Accessories Corporation (S.A.C) manufactures such a system, called a three dimensional ultrasonic digitizer. The system works by accurately measuring the transit time of a sound wave from a small spark gap source to a point microphone. Multiplying the transit time by the speed of sound in air, compensated for changes in temperature, produces the distance from the source to the receivers. The distances from the source to at least three receivers (referred to as slant ranges) with known orientation can then be triangulated to produce the coordinates of the source in the receiver coordinate system. Since we are trying to monitor the relative positions of two rigid bodies, a minimum of three sources and three receivers are required.

More specifically, the system works by triggering a spark gap which emits an audible wide band frequency pressure wave ("click"). At the same time a start signal is generated which turns on high frequency counters associated with each microphone. The microphones "listen" for a signal between 55 and 60 kilohertz and send a stop signal to the counters when the sound is received. A temperature sensitive transistor, mounted on a preamp box next to one of the microphones, monitors the ambient temperature and adjusts the number of clock cycles per centimeter accordingly. The only major constraint on this system is

that the spark gap source must have a clear line of sight to at least three microphones to determine its relative position in space.

Science Accessories offers two models of the three dimensional digitizer. Model 1 ($10,700) outputs only slant range distances which are accurate to ±0.1% of the measured slant range distance and are precise to within ±0.01 centimeters. Model 2 ($12,000) converts the slant range values into Cartesian coordinates and requires the microphones to be accurately positioned in a specific array. Both models come with four point microphones to allow system redundancy or to make sure at least three microphones meet the line of sight constraint.

4.3 Conclusions

Given the above alternatives for a reference system, microscope position tracking (Section 4.2.4) and the ultrasonic linkage (Section 4.2.5), and based on an estimate of performance and constraints it was determined that the ultrasonic linkage appeared to be the best choice because it meets all the physical constraints on the reference system and will not interfere with the surgical procedure, it will cost less than most of the other designs, and it incorporates a more elegant design. A Model 1 (slant range output) ultrasonic digitizer was purchased from S.A.C. with three spark gaps and an RS-232 serial communications board

to transmit the data to a host computer, an IBM PC XT. The important specifications are listed below.

1) The spark gap - microphone distance (slant range) is accurate to within ±0.1% of the measured distance.

2) The resolution or precision of the slant ranges are within ±0.01 centimeters.

3) The maximum slant range is approximately 250 centimeters.

4) The maximum sampling rate (transmitting data at 9600 baud) is approximately 30 points per second.

The accuracy of the digitizer was investigated further to determine its limitations.

Chapter 5 - Ultrasonic Linkage

This chapter describes the fundamental constraints on the digitizer based on the physics of sound propagation in air (5.1), the sensitivity of the digitizer to temperature variations (5.2) and counter error (5.3), and an ultrasonic linkage description (5.4).

5.1 Physics of Sound Propagation in Air

The purpose of this section is to determine the sensitivity of the speed of sound in air to various parameters such as temperature and relative humidity.

It is assumed that air behaves as an ideal gas for normal atmospheric pressures (valid up to several million Newtons per square meter) and that for sound propagation its compression as a pressure wave is isentropic (reversible and adiabatic). Applying the laws of thermodynamics to sound propagation in the operating room environment with relative humidity 20 to 60% and temperature of 19 to 24°C, gives the results in Table 5.1 below [11].

Table 5.1 - Speed of Sound in Air

T (°C)	ϕ	c (m/s)
19	20%	342.788
	60%	343.257
24	20%	346.150
	60%	346.816

This Table indicates that the speed of sound in air, c, is much more sensitive to variations in temperature than variations in relative humidity.

5.2 Sensitivity to Temperature

The sonic digitizer is based on the simple principle, d = ct, where d is the distance calculated in meters, c is the speed of sound in meters/second, and t is the transit time between firing the spark gap and sensing the signal at the microphone. Since the speed of sound in air is most directly a function of temperature and the temperature is only monitored at one of the microphone preamps, there must be some fundamental relationship between the variations in temperature over the path and the accuracy of the digitizer. Letting $A = kR/mw$ and $c = A\sqrt{T}$ (from Section 5.1) and applying the chain rule of differential calculus to d = ct, where k is the ratio of specific heats of air at constant temperature to that at constant volume, R = 8314.3 J/kg-mole-^{o}K is the universal gas constant, mw is the molecular weight in grams/mole , and T is the absolute temperature in ^{o}K,

$$d = At\sqrt{T},$$

$$\Delta d = \frac{\delta d}{\delta T}\Delta T + \frac{\delta d}{\delta t}\Delta t.$$

Since we are interested in the sensitivity of d with respect to changes in temperature within the active volume only, let $\Delta t = 0$.

$$\Delta d = \frac{\delta d}{\delta T}\Delta T = At\Delta T/2\sqrt{T}$$

$$\text{relative \% change in d} = \Delta d/d$$

$$\Delta d/d = At\Delta T/2d\sqrt{T} = At\Delta T/2At\sqrt{T}\sqrt{T}$$

$$\Delta d/d = \Delta T/2T$$

Since the accuracy of the system is $\pm$ 0.1% of the measured distance for slant range calculations,

$$0.001 = \Delta T/2T,$$

$$\Delta T = 0.002T(^{\circ}K),$$

$$\Delta T_{min} = 0.002(283.15^{\circ}K) = 0.57^{\circ}C,$$

$$\Delta T_{max} = 0.002(297.59^{\circ}K) = 0.60^{\circ}C,$$

$$\Delta T = 0.6^{\circ}C.$$

Therefore, ΔT is an estimate of the amount the temperature can vary over the sonic path and deviate from the temperature determined at the microphones. This indicates that the percent change in the slant range values (specification 1 from Section 4.3) can tolerate a temperature variation of up to 0.6°C before exceeding $\pm$0.1%. This assumes that temperature is the only factor affecting the speed of sound in air, which was concluded in Section 5.1.

5.3 Sensitivity to Counter Error

The basic counter clock cycle frequency, 3.6406 MHz, is adjusted to 100 counts per centimeter or 0.1 mm per count, based on the temperature reading at the microphones. Therefore, since the counters can be in error by up to one clock cycle due to the counter resolution, the counter error is $\pm$ 0.01 centimeters.

5.4 General Ultrasonic Linkage Design

The reference system must determine the position of the microscope and its focal plane with respect to the patient's head and CT scans given the distances between spark gaps and microphones. The purpose of this section is to determine the appropriate placement and orientation of the spark gaps given the constraints of the ultrasonic digitizer.

As mentioned in Section 4.2.4.1, at least six pieces of information must be known about a rigid body (microscope) to locate it in a fixed coordinate system (CT). In Section 4.2.3 it was determined that the coordinates of three points (nine pieces of information) are easier to determine than relative angles and sufficient to locate the position of the microscope. Therefore, three spark gaps are needed in addition to at least three microphones.

Physical and aseptic constraints in the operating room would prevent mounting either the microphones or the sparks

gaps on the patient's head to determine the relative microscope-CT scan positions. These constraints also indicate that mounting the microphones (connected to 3x5x13 centimeter pre-amp boxes) on the operating room ceiling between the light tracks and air vent, and mounting the spark gaps on the microscope would probably be the most acceptable design.

The orientation and separation of the spark gaps are important as errors in the slant ranges can produce errors at the focal point. The optimal spatial distribution of three points would be an equilateral triangle since random errors at each point are more likely to cancel and reduce the error at the geometric center than the errors resulting from other distributions [3]. For example, three points in an isosceles triangle would magnify the error along the line from the apex bisecting the base. The optimal spark gap separation (S) and distance (D) from the geometric center of the spark gaps to the focal point (F) can be determined for an error at each point (e). If the three spark gaps lie on an equilateral triangle in the x-y plane (See Figure 5.1) and the focal point lies in the z direction, the maximum error at F in the x-z plane (e_{xz}), given a maximum error at each point (e), can be determined by similar triangles. See Figure 5.2. Point F' is the new position of the focal point due to e.

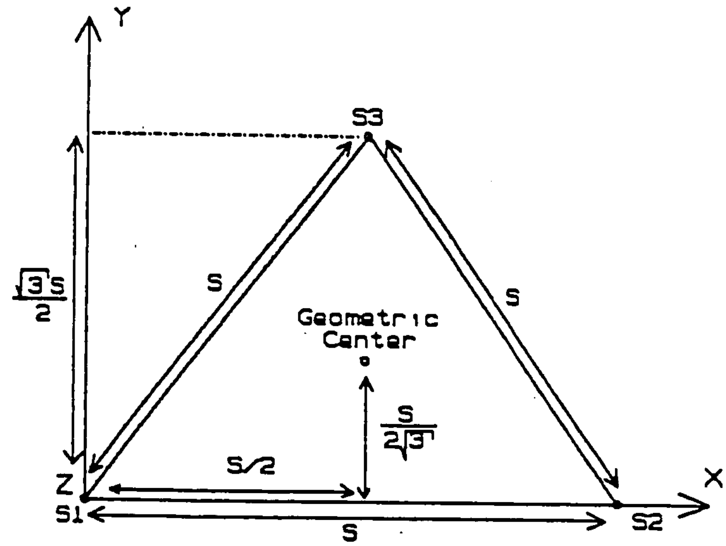


Figure 5.1 - Spark Gap Separation

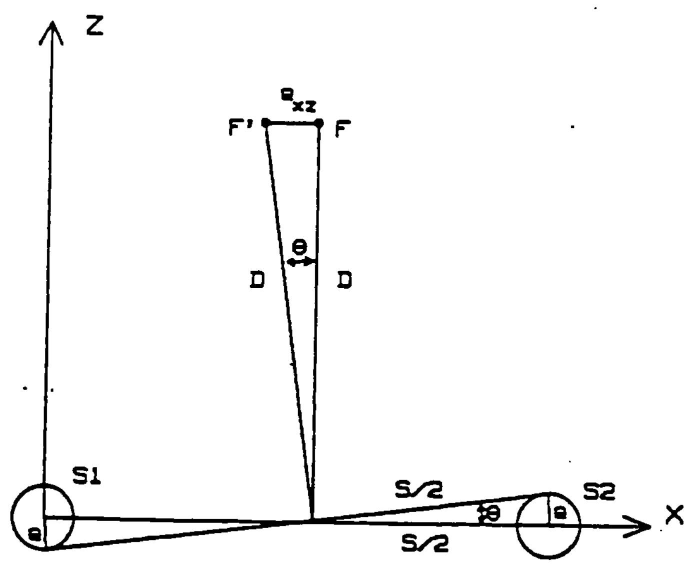


Figure 5.2 - XZ Plane Error

$$e_{xz}/e = D/S/2$$

$$e_{xz} = 2De/S$$

Applying the same error to spark gap 3 and pivoting about the line between spark gaps 1 and 2 produces a focal point error (F′ to F″) in the y-z plane, e_{yz}, which can also be determined by similar triangles. See Figure 5.3.

$$e_{yz}/e = G/\sqrt{3}\ S/2,$$

$$e_{yz} = 2Ge/\sqrt{3}\ S,$$

$$G = \sqrt{D^2 + (S/2\sqrt{3}\ )^2} = \sqrt{D^2 + S^2/12},$$

$$e_{yz} = 2e\sqrt{D^2 + S^2/12}\ /\sqrt{3}\ S,$$

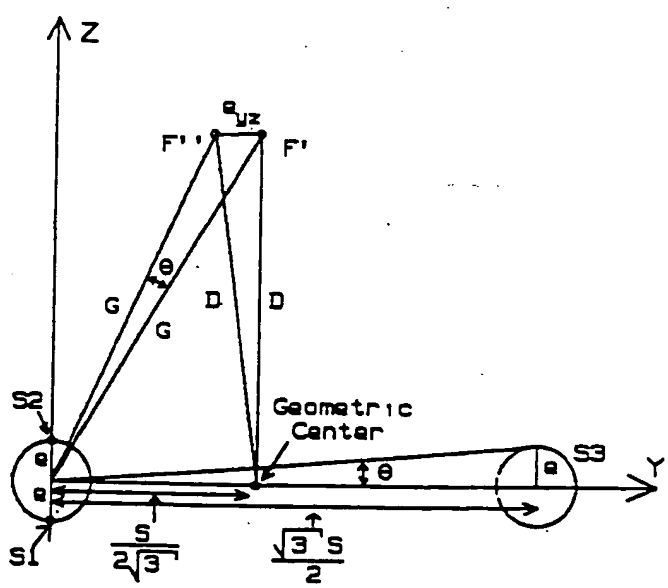


Figure 5.3 - YZ Plane Error

Since angle θ can be considered very small, these error vectors can act perpendicularly to each other. Therefore, their magnitude is given by:

$$e_{max} = \sqrt{e_{xz}^2 + e_{yz}^2},$$
$$e_{max} = \sqrt{4D^2e^2/S^2 + 4e^2(D^2 + S^2/12)/3S^2},$$
$$e_{max} = e\sqrt{48(D/S)^2 + 1}/3.$$

This relationship shows that the minimum error at the focal point occurs when S is a maximum and D is a minimum. This makes sense, as minor microscope movements will produce greater spark gap displacements for larger values of D and, therefore, produce greater effective resolution in determining the location of the focal point. The spark gap separation, however, is limited by the required mobility of the microscope. The sterile draping and physical constraints of the operating room limit the spark gap separation to approximately 30 centimeters. Minimizing the lever arm, D, to zero also cannot be achieved because of physical operating constraints. Depending on the position of the patient, two different distances are practical. With the patient in a sitting position the lever arm can be no less than approximately 45 centimeters and with the patient in a supine position no less than 25 centimeters.

The general registration procedure involves CT scanning the patient with at least three fiducials attached to the head. With the spark gaps mounted on the microscope and

microphones mounted on the ceiling, the patient's head will be placed in a rigid clamp which anchors the position of the fiducials with respect to the microphones. See Figure 5.4. The positions of the microphones with respect to the CT scans are then determined by focusing on each fiducial (see Section 4.2.3) and will be discussed in detail in Chapter 6.

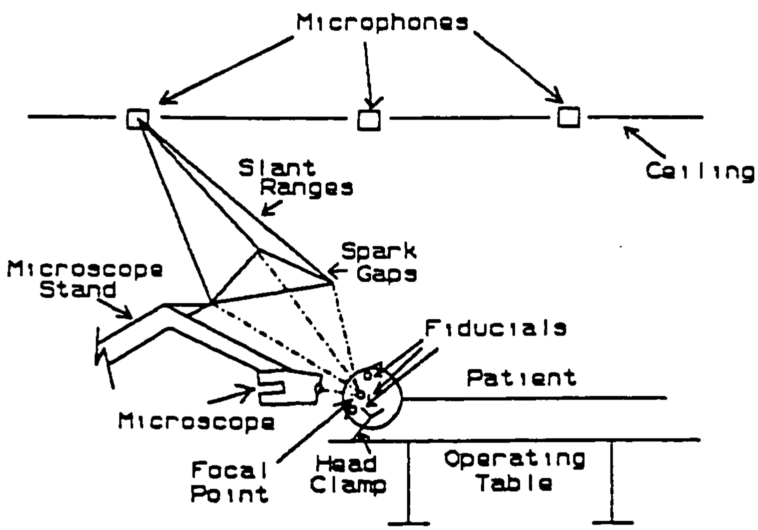


Figure 5.4

Fiducial - Microphone Relationship

Chapter 6 - Reference Frames

This chapter can be divided into two major parts. The first part describes three possible reference frames considered for the calculations of the reconstructed CT image at the focal plane - the CT, digitizer, and microscope coordinate systems. Each of these offer advantages and disadvantages which are outlined in sections 6.1 - 6.3. The second part (section 6.4) details the reference system design including the equations and algorithm references necessary for determining the spark gap - focal plane relationship (6.4.1) and the conversion of focal points to CT coordinates (6.4.2). Also included in section 6.4.1 is the description of a fourth reference frame, an oblique spark gap coordinate system. Section 6.4.3 describes the general reference system procedure.

6.1 CT Coordinate System

The CT slices are stored in a CT Cartesian coordinate system established by the CT scanner. The z axis corresponds to the transverse body axis for conventional scans where the CT gantry is zero degrees from the vertical. The CT scans are slices in the x-y plane. See Figure 6.1.

The advantage of performing reference and reconstruction calculations in the CT coordinate system is that all the information (CT data) is in that reference

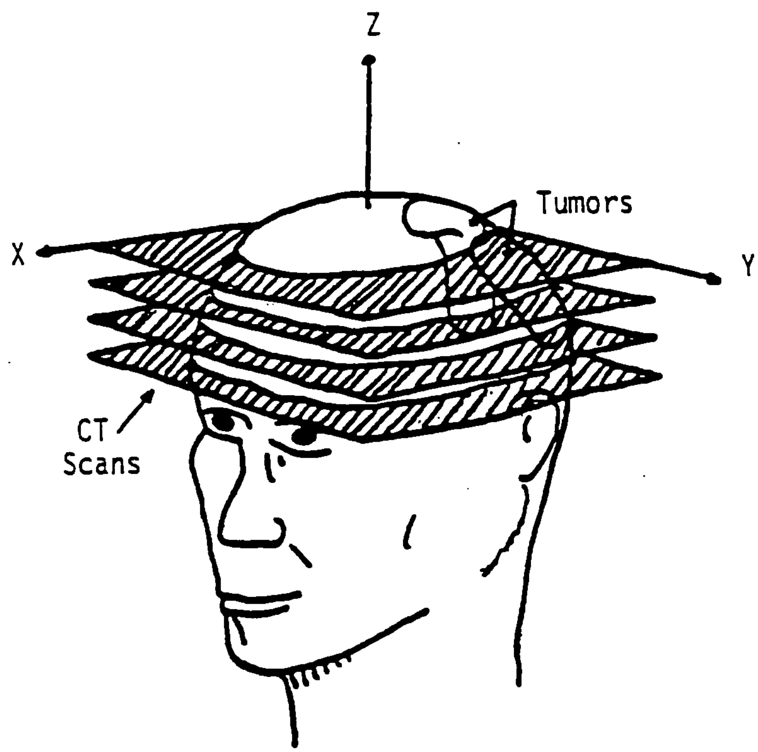


Figure 6.1 - CT Coordinate System

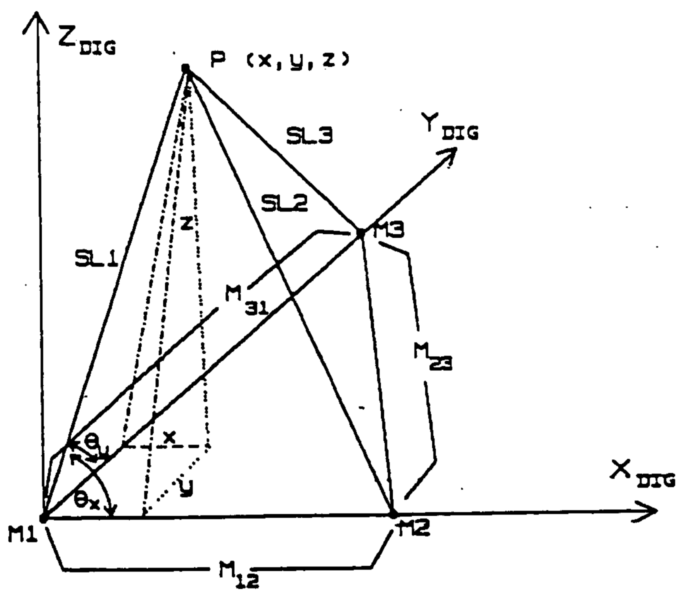
frame, requiring few transformations between coordinate frames, which can take a lot of processor time and introduce error to the system. The disadvantage of working in CT coordinates is that it restricts the reference system to one that, in practice, may be awkward or undesirable. Further investigation will determine if this is true.

6.2 Digitizer Coordinate System

A digitizer coordinate system can be established to determine the coordinates of the spark gaps with respect to the microphones. As mentioned in Section 4.2.5, triangulation of the slant range data given three

orthogonally placed microphones whose separation is known determines the Cartesian coordinates of the spark gaps with respect to the microphones. See Figure 6.2. The microphones do not necessarily have to be orthogonal; an oblique coordinate system can also be established.

The spark gaps (therefore, the microscope and focal plane) are repositioned within the digitizer coordinate system established by the microphones on the operating room ceiling. The patient's head and CT scans are also within



$$\cos\theta_x = (M_{12}^2 + SL1^2 - SL2^2)/2SL1M_{12}$$
$$\cos\theta_y = (M_{31}^2 + SL1^2 - SL3^2)/2SL1M_{31}$$
$$x = SL1\cos\theta_x = (M_{12}^2 + SL1^2 - SL2^2)/2M_{12}$$
$$y = SL1\cos\theta_y = (M_{31}^2 + SL1^2 - SL3^2)/2M_{31}$$
$$z = \sqrt{SL1^2 - x^2 - y^2}$$

Figure 6.2

Digitizer Coordinate Calculations

this space, which may make calculations in the digitizer reference frame easier to understand. The disadvantages of working in digitizer coordinates are that all the CT data must be transferred to the digitizer system and the exact microphone separations must be known.

6.3 Microscope Coordinate System

The reconstructed CT scan must eventually be displayed in the microscope as a two dimensional CRT image. This involves converting the reconstructed slice from a matrix of three coordinates to one of two coordinates, (x,y). A microscope coordinate system could represent the focal plane as x and y, normal to the optical axis with the origin at the focal point. See Figure 6.3. This technique requires a transformation of coordinates because the microscope coordinate system will be constantly changing with respect to the location of the microphones and CT scans as the surgeon moves the microscope. Regardless of the reference frame used for reconstructing the slice, in order to display the proper image, the slice must be transformed into microscope coordinates. The advantage of transforming all the data and performing the calculations in the microscope coordinate system is that if the surgeon only moves the microscope slightly or along the optical axis, the reconstruction calculations could be greatly reduced and

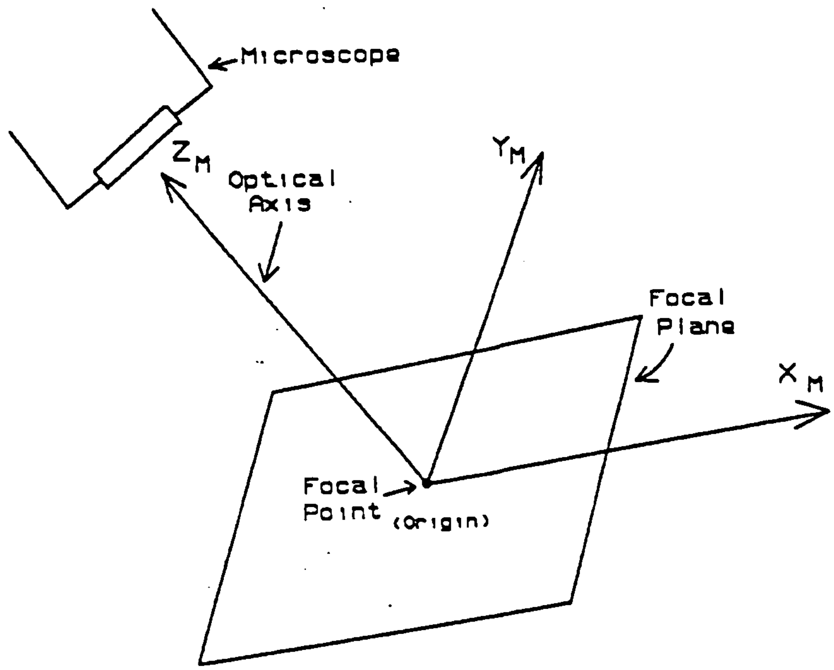


Figure 6.3

Microscope Coordinate System

allow the surgeon to quickly call up successive new slices for viewing.

6.4 Reference System Design

This section describes an optimal reference system design and the goals of such a system.

The number of CT slices and whether or not grey scale information will be processed (only contours will be reconstructed initially) will determine the appropriate use of the CT coordinate system. Since the CT data will be manipulated by the Treatment Planning Computer, it is probably best to perform the reconstructions in the CT

coordinate system. Since we know that the reconstructed slice must be displayed in the microscope, the microscope coordinate system must be established for transforming the new slice at each microscope position. A digitizer coordinate system is unnecessary because the positions of the microscope, sparks gaps and microphones can be determined in CT coordinates.

The general reference system design will involve determining the position of the focal plane in CT coordinates. Since this is an initial design the information needed by the Treatment Planning Computer to reconstruct and display a CT image can be divided into three parts.

1) The equation of the focal plane in CT coordinates is necessary to determine the appropriate reconstructed image.

2) The CT coordinates of the focal point must be determined such that the center of the reconstructed slice will be properly displayed.

3) Since the equation of the focal plane and the CT coordinates of the focal point do not uniquely define the orientation of the focal plane about the optical axis, more information is needed. The three direction cosines of the Y_M axis of the microscope coordinate system with respect to the X_{CT}, Y_{CT} and Z_{CT} axes will provide the necessary angular information to orient the reconstructed CT image. See Figure 5.4.

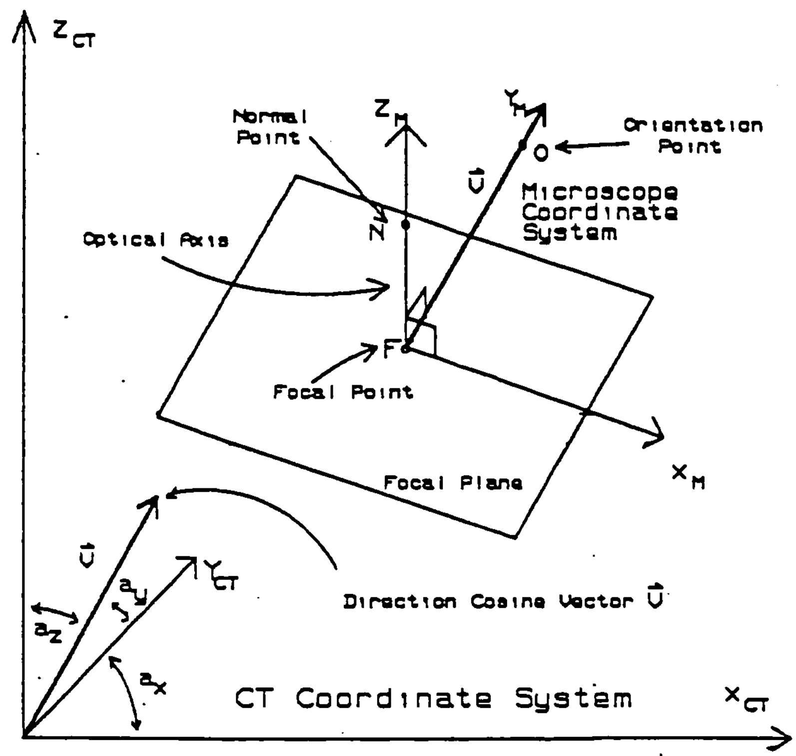


Figure 6.4.- Reference System Design

6.4.1 Spark Gap - Focal Plane Relationship

The patient is anchored to the operating table generally in one of two positions - sitting or supine (see section 5.4). The physical and sterile constraints of the operative procedure restrict the placement of the three spark gaps such that two spark gap holder brackets are necessary, fixing the position of the spark gaps with respect to the microscope and focal plane in each case. Therefore, the first step in the reference procedure is to determine the relative positions of the spark gaps and the focal plane for both the sitting and supine cases.

The information needed to calculate the equation of the focal plane, the CT coordinates of the focal point, and the three direction cosines is explained below.

Three simple ways to define a plane include determining: 1) the coordinates of three non-colinear points in the plane, 2) a normal vector to the plane and one known point in the plane, or 3) the coordinates of two points along a normal line, one of which is in the plane. In order to uniquely define the focal plane, we also need to know the orientation of the plane about the optical axis (focal point). Therefore, the coordinates of at least three points are needed to define and orient the focal plane in CT coordinates (X_{CT}, Y_{CT}, Z_{CT}): the focal point, a point along the optical axis (normal point) and a point in the focal plane (orientation point). See Figure 5.4.

6.4.1.1 Focal Point

As the first step this section introduces an oblique spark gap coordinate system and describes the equations necessary to determine the focal point with respect to the spark gaps.

One technique is to calculate the coordinates of the focal, normal and orientation points in an oblique coordinate system defined by the vertices of the equilateral spark gap triangle (explained in section 5.4). See Figure 6.5. The locations of the focal, normal and orientation

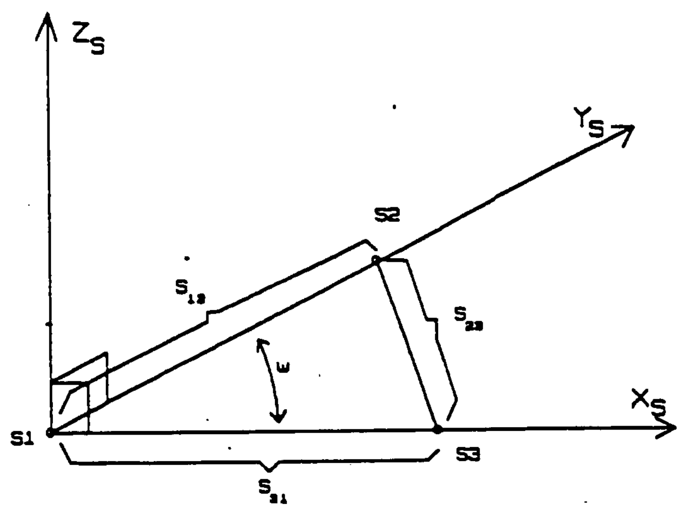


Figure 6.5
Oblique Spark Gap Coordinate System

points must be determined with respect to the fixed spark gaps, independent of the microscope's position. First we will define the oblique spark gap coordinate system. The origin is at spark gap 1 (S1), the X_S axis is along the line connecting S1 to spark gap 3 (S3), the Y_S axis is along the line connecting S1 to spark gap 2 (S2), and the Z_S axis is along the line from the S1 perpendicular to the spark gap plane. The obliquity angle, w, can be calculated by applying the Law of cosines to the measured spark gap separations S_{12}, S_{23}, and S_{31}:

$$\cos(w) = (S_{12}^2 + S_{31}^2 - S_{23}^2)/2S_{12}S_{31} \quad (6.1).$$

As will be shown below the oblique spark gap coordinates of the focal point can be calculated by focusing the microscope on the tip of an additional spark gap. With

the microphones on the ceiling, the digitizer can determine the slant range distances from the four spark gaps to the three microphones. The first task is to determine the location of the microphones in the oblique spark gap coordinate system. This can be done based on the slant range distances from the three microscope mounted spark gaps to the three microphones. Once the microphone coordinates in the spark gap coordinate space are known, the focal point can be determined. The appropriate equations are found as follows.

Figure 6.6 shows the relationships between the slant range distances (SL_i) and the spark gap coordinates $P(x_S, y_S, z_S)$ for one microphone. The perpendicular projections of SL_1 on the X_S and Y_S axes (P_x, P_y) are determined by applying the Law of cosines:

$$P_x = SL_1 \cos(a_1), \quad (6.2)$$

$$P_x = (S_{31}{}^2 + SL_1{}^2 - SL_3{}^2)/2S_{31}, \quad (6.3)$$

Similarly,

$$P_y = (S_{12}{}^2 + SL_1{}^2 - SL_2{}^2)/2S_{12}. \quad (6.4)$$

Coordinates x_s and y_s can be calculated from:

$$\cos(w) = (P_x - x_s)/y_s = (P_y - y_s)/x_s, \quad (6.5)$$

therefore,

$$x_s = (P_y - y_s)/\cos(w), \quad (6.6)$$

$$y_s = (P_x - x_s)/\cos(w). \quad (6.7)$$

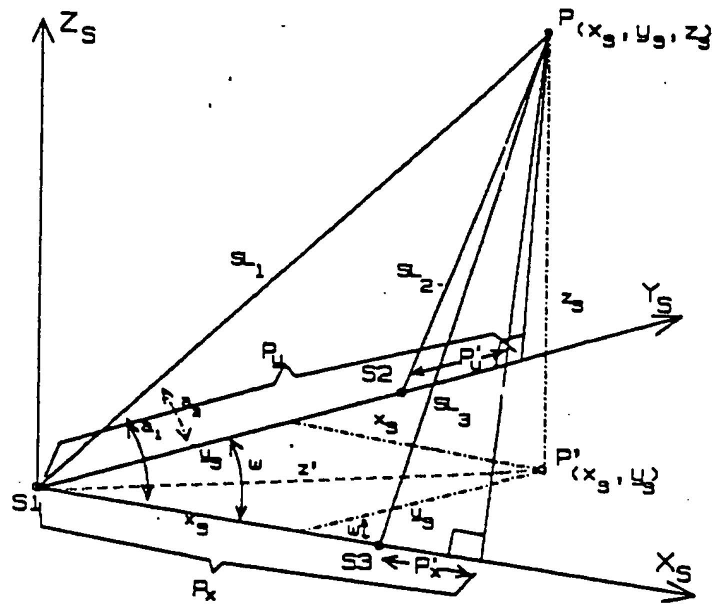


Figure 6.6 - Spark Gap Coordinates

Substituting (6.7) into (6.6):

$$x_s = (P_x - P_y\cos(w))/\sin^2(w). \quad (6.8)$$

Alternately, substituting (6.6) into (6.7) yields:

$$y_s = (P_y - P_x\cos(w))/\sin^2(w). \quad (6.9)$$

z' can be found by applying the Law of cosines:

$$z'^2 = x_s^2 + y_s^2 - 2x_s y_s\cos(\Pi - w) \quad (6.10).$$

The coordinate z_s can then be found by applying the Pythagorean theorem:

$$z_s^2 = SL_1^2 - z'^2 \quad (6.11),$$

$$z_s = \sqrt{SL_1^2 - x_s^2 - y_s^2 - 2x_s y_s\cos(w)} \quad (6.12).$$

Therefore we have determined the coordinates of one microphone in the spark gap coordinate system. The coordinates of the other two microphones are found

similarly. In summary, the equations needed to calculate the oblique spark gap coordinates of the three microphones are:

1) apply 6.1 to determine w,
2) apply 6.3 and 6.4 to determine P_x and P_y,
3) apply 6.8 and 6.9 to determine x_s and y_s,
4) apply 6.12 to determine z_s.

Once the oblique spark gap coordinates of the three microphones are determined, the coordinates of the focal point (spark gap 4) can be calculated by solving three nonlinear equations for the distances between each microphone and the focal point. See Figure 6.7. M_1, M_2, and M_3 represent microphones 1, 2, and 3; F is the focal point whose oblique coordinates (x_s,y_s,z_s) are unknown; and D_1, D_2 and D_3 are the slant range distances between F and M_1, M_2 and M_3. The equation relating the distances, D_i, between F and the microphones in oblique spark gap coordinates (for i = 1 to 3) is:

$$D_i^2 = (x_s-x_{s_i})^2+(y_s-y_{s_i})^2+(z_s-z_{s_i})^2 \\ +2(x_s-x_{s_i})(y_s-y_{s_i})\cos(w). \quad (6.13)$$

Solving these three equations by an iterative Newton's method (see Chapter 9) for x_s,y_s,z_s will give the oblique coordinates of the focal point in the spark gap coordinate system.

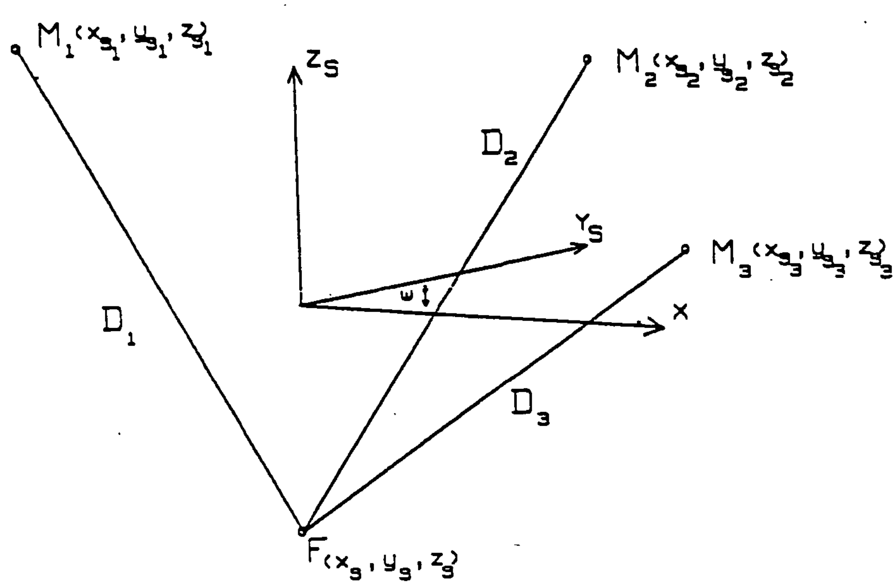


Figure 6.7 - Focal Point Calculations

6.4.1.2 Normal Point

This section describes the equations and procedures needed to determine the oblique spark gap coordinates of the normal point along the optical axis. The first-step involves establishing a Cartesian coordinate system (indicated by subscript F) that is fixed with respect to the microphones by focusing the microscope on three points on a piece of plexiglas where the coordinates of the three points are known. This will allow both the normal and orientation points (see section 6.4.1.3) to be determined independent of the oblique spark gap coordinate system. Once this is known, the fixed coordinates of the focal point can be calculated for any microscope position since its location is

known with respect to the spark gaps (oblique spark gap coordinates) and the location of the spark gaps are known with respect to the microphones (digitizer slant range distance). Assuming that the focusing knob of the microscope accurately moves the focal point along the optical axis, the fixed coordinates of a normal point can be determined and then its coordinates in the oblique spark gap system referred to the original focal point.

To determine the coordinates of the three microphones in the fixed coordinate space we rely on the fact that the distances between the focal point and microphones can now be calculated. Refer to Figure 6.8. The oblique spark gap coordinates of the focal point (x_{fp}, y_{fp}, z_{fp}) are known and fixed for each spark gap bracket (sitting or supine), and by applying the steps outlined in 6.4.1.1 (Equations 6.8, 6.9 and 6.12) the oblique spark gap coordinates of each microphone (x_m, y_m, z_m) can be calculated given the three slant range distances SL_1, SL_2 and SL_3. The distances between each microphone and the focal point can be determined by applying the oblique distance formula (Equation 6.14)

$$D^2 = (x_m - x_{fp})^2 + (y_m - y_{fp})^2 + (z_m - z_{fp})^2 + 2(x_m - x_{fp})(y_m - y_{fp})\cos(w) \quad (6.14).$$

By focusing on three points (P_1, P_2, P_3 in Figure 6.9) whose coordinates are known in the fixed coordinate system

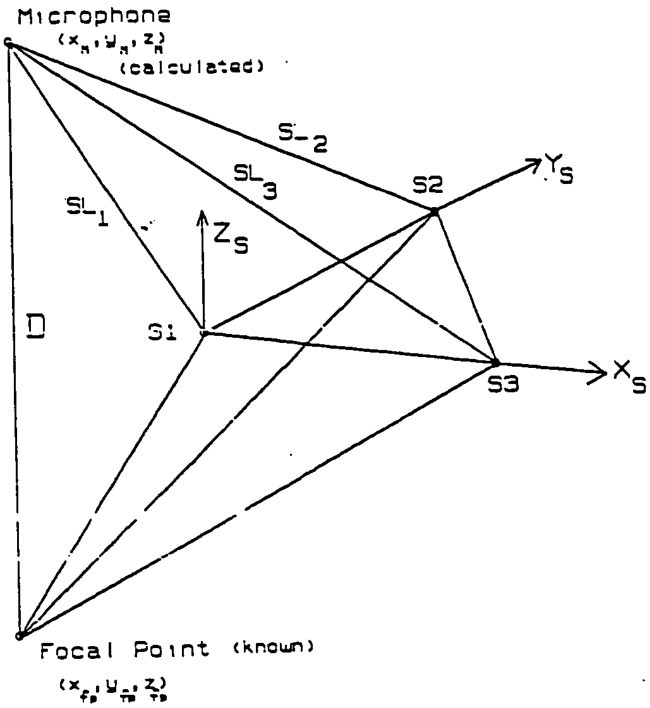


Figure 6.8 - Focal Point - Microphone Distance

and calculating each point - microphone distances (D_{11} - D_{33}) using Equation 6.14, the fixed coordinates of the microphones (M_1, M_2, M_3) can be determined by solving three nonlinear equations for each microphone. M_1-M_3 represent the microphones, P_1-P_3 represents the points in a fixed Cartesian coordinate system, and D_{i1}-D_{i3} represent the distances calculated between microphone i ($x_{m_i}, y_{m_i}, z_{m_i}$) and P_1-P_3. The fixed coordinates of microphone i can be calculated by solving the three (j = 1 - 3) nonlinear equations below using Newton's method given the coordinates of P_j and distances D_{ij}:

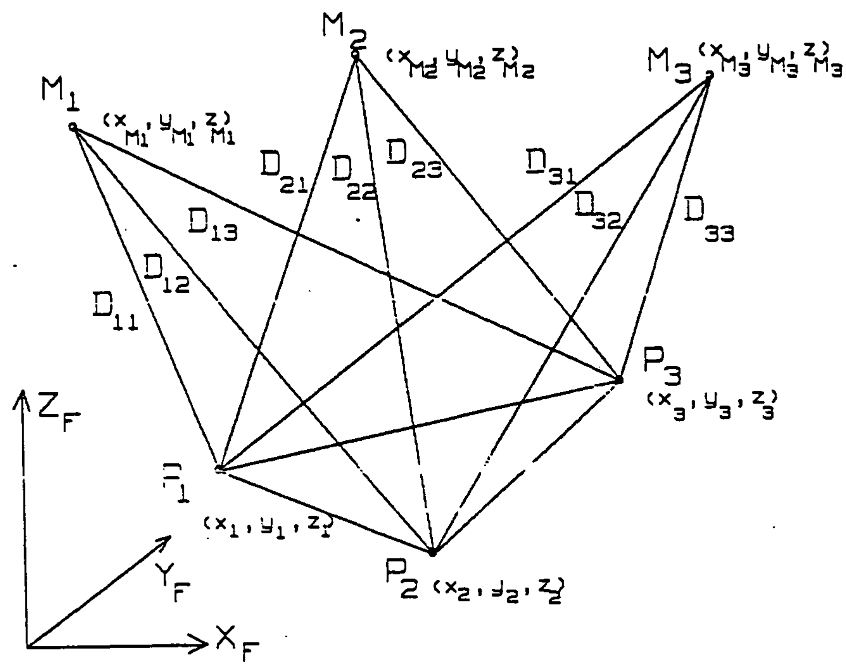


Figure 6.9 - Microphone Coordinates

$$(x_{m_i}-x_j)^2+(y_{m_i}-y_j)^2+(z_{m_i}-z_j)^2 = D_{ij}^2 \quad (6.15).$$

Once the fixed coordinates of each microphone are known, the fixed coordinates of the focal point can be determined independent of the microscope's position. In order to calculate the fixed coordinates of a normal point the oblique coordinates of the three microphones $(x_{ms_i}, y_{ms_i}, z_{ms_i})$ must be determined by applying Equations 6.8, 6.9 and 6.12 with the microscope in a fixed position. Then by adjusting the focusing knob and moving the microscope along the optical axis, as shown in Figure 6.10, the spark gaps will now be at points S1', S2' and S3' and

the new focal point (F') will be at the normal point, N. The fixed coordinates of N (x_n, y_n, z_n) can be found by solving Equation 6.14 for the normal point - microphone distances, D_i, and then solving the three (j=1 - 3) nonlinear equations by Newton's method for x_n, y_n and z_n given D_i, and x_{m_i}, y_{m_i} and z_{m_i}:

$$(x_n-x_{m_i})^2+(y_n-y_{m_i})^2+(z_n-z_{m_i})^2 = D_i^2 \quad (6.16).$$

Up to here we know the following:

1) the fixed coordinates of the three microphones - $(x_{m_i}, y_{m_i}, z_{m_i})$,

2) the oblique coordinates of the three microphones with respect to the spark gaps (and microscope) at S1, S2 and S3, Figure 6.10 - $(x_{ms_i}, y_{ms_i}, z_{ms_i})$,

3) the fixed coordinates of the normal point, N - (x_n, y_n, z_n).

The oblique coordinates of N (x_{ns}, y_{ns}, z_{ns}) with the spark gaps at S1, S2 and S3 of Figure 6.10, can be calculated by solving the three nonlinear equations by Newton's method for x_{ns}, y_{ns} and z_{ns}, given the normal point - microphone distances D_i (from Equation 6.15) and the oblique microphone coordinates $(x_{ms_i}, y_{ms_i}, z_{ms_i})$:

$$(x_{ns}-x_{ms_i})^2+(y_{ns}-y_{ms_i})^2+(z_{ns}-z_{ms_i})^2+$$
$$2(x_{ns}-x_{ms_i})(y_{ns}-y_{ms_i})\cos(w)=D_i^2 \quad (6.17)$$

In summary, the steps needed to calculate the oblique spark gap coordinates of the normal point are:

1) determine the coordinates of the three microphones in a fixed coordinate system by focusing the microscope on three points whose fixed coordinates are known, and applying Equations 6.8, 6.9, 6.12, 6.14 and 6.15,

2) determine the fixed coordinates of point N by moving the microscope along the optical axis (focusing knob) and applying Equations 6.14 and 6.16,

3) calculate the oblique coordinates of point N by solving Equation 6.17 for x_{ns}, y_{ns} and z_{ns}. See Figure 6.10.

6.4.1.3 Orientation Point

This section describes the steps and equations necessary to calculate the oblique coordinates of an orientation point, O, along the Y_M axis of the microscope coordinate system (see Figure 6.4). This point, in combination with the focal and normal points will determine the orientation of the focal plane about the optical axis by indicating the "top" of the displayed image as seen through the microscope. The ocular crosshairs of the microscope are instrumental in focusing the microscope, and determining the microscope coordinate system. See Figure 6.11.

The oblique coordinates of the orientation point can be found by following essentially the same steps in determining

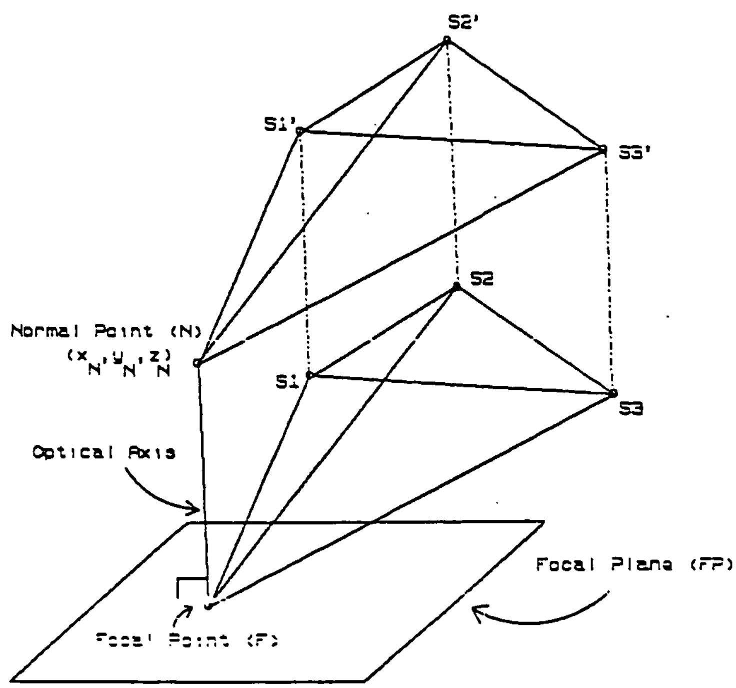


Figure 6.10 - Normal Point

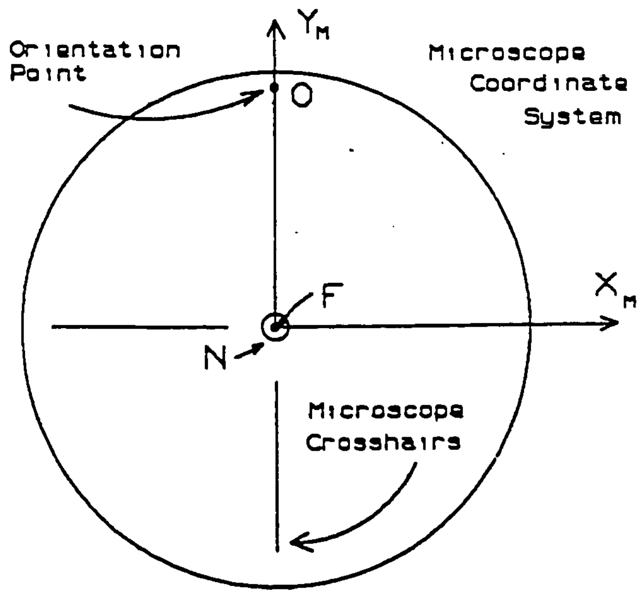


Figure 6.11 - Orientation Point

the normal point. The normal point is only used to determine the equation of the focal plane and its distance from the focal point (although limited by the range of the focusing knob) is arbitrary as long as it falls along the optical axis. Likewise, the distance between the focal and orientation point is arbitrary as long as the line connecting them is 90° to the optical axis of the microscope coordinate system.

To take advantage of the fixed coordinate system established in section 6.4.1.2, we will assume the fixed coordinates of the microphones are known ($x_{m_i}, y_{m_i}, z_{m_i}$) and that the oblique coordinates of the microphones ($x_{ms_i}, y_{ms_i}, z_{ms_i}$) have been determined such that the fixed coordinates of the focal point (F) and a point (P) located along the Y_M axis of the microscope coordinate system are also known. See Figure 6.12. As with the normal point, the fixed coordinates of an orientation point must be determined first.

This can be accomplished by projecting the known point P (x_p, y_p, z_p) onto the focal plane and determining its new fixed coordinates. If the microscope is focused with minimum parallax error such that the Y_M ocular crosshair is closely aligned along the line between F and P, then the new

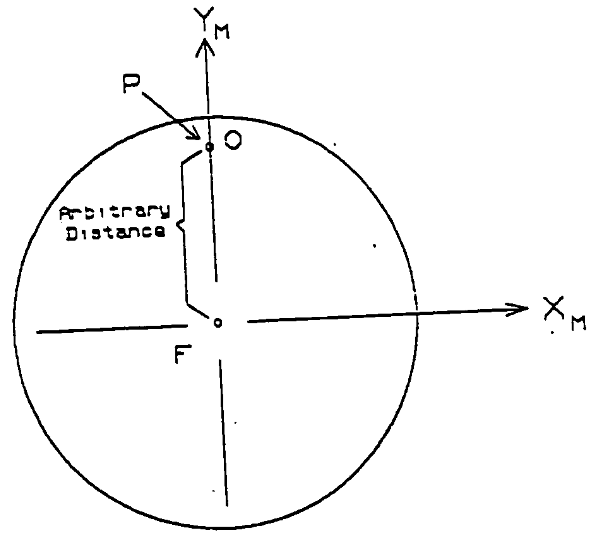


Figure 6.12 - Focal Plane Orientation

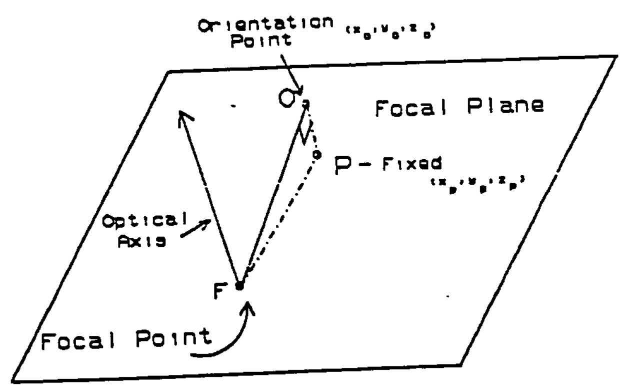


Figure 6.13 - Projected Orientation Point

projected point can be considered the orientation point. See Figure 6.13.

In order to determine the fixed coordinates of O, (x_o, y_o, z_o) the equation of the focal plane must be established. The normal vector along the optical axis can be represented in the fixed coordinate system by the equation:

$$\vec{N} = A\hat{i}_f + B\hat{j}_f + C\hat{k}_f \quad (6.18)$$

where $\hat{i}_f$, $\hat{j}_f$ and $\hat{k}_f$ are the unit vectors along the fixed X, Y and Z axes. The coefficients A, B and C can be determined from the fixed coordinates of the normal (x_n, y_n and z_n) and focal (x_{fp}, y_{fp}, z_{fp}) points.

$$\vec{N} = (x_n - x_{fp})\hat{i}_f + (y_n - y_{fp})\hat{j}_f + (z_n - z_{fp})\hat{k}_f.$$

(6.19)

Since $\vec{N}$ is a vector normal to the focal plane, then for any vector $\vec{V} = (X_f, Y_f, Z_f)$ in the plane:

$$\vec{N} \cdot (\vec{V} - \vec{V}_f) = 0 \quad (6.20)$$

where $\vec{V}_f$ is the focal point vector (x_{fp}, y_{fp}, z_{fp}).

Therefore,

$$(x_n - x_{fp})(X_f - x_{fp}) + (y_n - y_{fp})(Y_f - y_{fp}) + (z_n - z_{fp})(Z_f - z_{fp}) = 0$$

(6.21)

is the equation of the focal plane in the fixed coordinate system. In order to calculate the fixed coordinates (x_o, y_o, z_o) of the projected point $P(x_p, y_p, z_p)$, the equation of the line through P normal to the focal plane must be determined. It is given by:

$$(x_o - x_p)/A = (y_o - y_p)/B = (z_o - z_p)/C \quad (6.22)$$

where A, B and C are the normal vector coefficients. If we let this common ratio equal t:

$$x_o = tA + x_p, \quad (6.23)$$
$$y_o = tB + y_p, \quad (6.24)$$
$$z_o = tC + z_p, \quad (6.25)$$

which are the parametric equations of the line. Substituting x_o, y_o and z_o into the equation of the focal plane where D is a constant:

$$Ax + By + Cz = D,$$
$$A(tA+x_p) + B(tB+y_p) + C(tC+z_p) = D,$$
$$t = (D - Ax_p - By_p - Cz_p)/(A^2+B^2+C^2). \quad (6.26)$$

Substituting Equation 6.26 into 6.23, 6.24 and 6.25 yields the fixed coordinates of the projected orientation point (x_o, y_o, z_o) [45]. The oblique coordinates of O with the spark gaps at S1, S2 and S3 of Figure 6.10, can be calculated by solving the three nonlinear equations by Newton's method for x_{os}, y_{os} and z_{os} given the orientation

point - microphone distances D_i (from Equation 6.15) and the oblique microphone coordinates ($x_{ms_i}, y_{ms_i}, z_{ms_i}$):

$$(x_{os}-x_{ms_i})^2+(y_{os}-y_{ms_i})^2+(z_{os}-z_{ms_i})^2$$
$$+2(x_{os}-x_{ms_i})(y_{os}-y_{ms_i})\cos(w) = D_i^2 \quad (6.27)$$

In summary, the steps needed to calculate the oblique spark gap coordinates of the orientation point are:

1) determine the fixed coordinates of point O by projecting point P onto the focal plane using Equations 6.22-6.26,

2) calculate the oblique coordinates of point O by solving equations 6.27 for x_{os}, y_{os} and z_{os}.

The relationship between the oriented focal plane and the spark gaps can now be defined by the oblique spark gap coordinates of the focal, normal and orientation points, independent of the position of the microscope.

6.4.2 Focal Points in CT Coordinates

Now that the relationship between the spark gaps and the focal points has been established, the general reference system procedure must be described.

6.4.2.1 Registration Procedure

The next step is to relate the CT scans and CT coordinate system with respect to the microphones and,

therefore, the focal, normal and orientation points. As mentioned in Section 4.2.3, three CT-detectable fiducials can be attached to the patient's head and their coordinates determined in the Cartesian CT coordinate system. By applying the principles of Section 6.4.1.2, the fiducials would represent P_1, P_2 and P_3 and the CT axes would represent the fixed axes of Figure 6.9. The coordinates of the microphones can be found in the CT coordinate system by focusing on each of the fiducials and solving Equations 6.15. At this stage we assume the patient's head will remain fixed during the rest of the procedure, e.g. that the patient is anesthetized and anchored in the head clamp (fiducials fixed with respect to the microphones).

6.4.2.2 Focal Plane Determination

With the microphone coordinates known, the neurosurgeon can perform the craniotomy and bring in the microscope when needed. Once the microscope is focused, the digitizer and an IBM PC XT computer will determine the slant range distances and the coordinates of focal, normal and orientation points calculated in the CT coordinate system. This is achieved by solving (i = 1 to 3):

$$(x_p-x_{m_i})^2+(y_p-y_{m_i})^2+(z_p-z_{m_i})^2 = D_{p_i}^{\ 2} \quad (6.28)$$

for x_p, y_p, z_p, the focal, normal and orientation points, using a Newton's method, given D_p (the distances from each

point to the microphones), which is determined by the oblique distance formula.

The equation of the focal plane can be determined by applying Equation 6.21, and the coordinates of the focal point are known such that the reconstructed CT image is appropriately centered. The orientation of the focal plane about the focal point must now be calculated. The three direction cosines of the vector from the focal point to the orientation point will provide enough information. See Figure 6.14. The vector in the CT coordinate space is:

$$\vec{T} = (x_o - x_{fp})\hat{i} + (y_o - y_{fp})\hat{j} + (z_o - z_{fp})\hat{k} \quad (6.29)$$

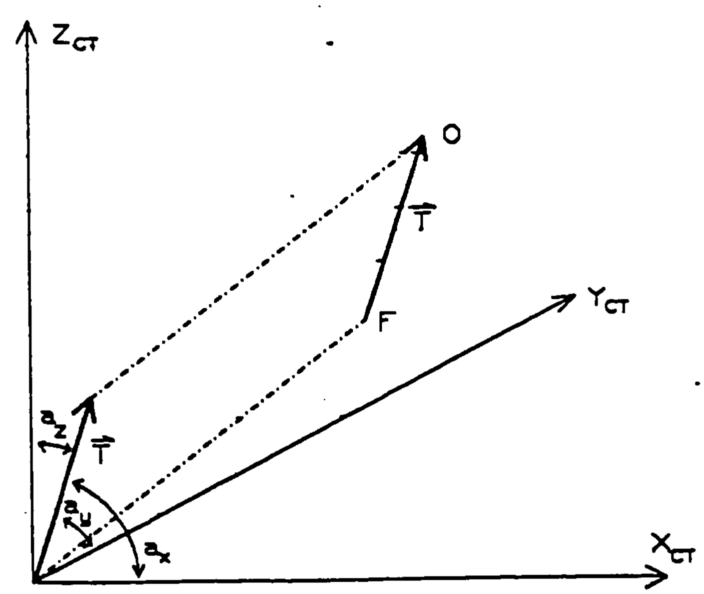


Figure 6.14 - Direction Cosines

Step 2 CT Scanning

CT scan the patient with three CT-detectable fiducials in place and determine their coordinates in the CT coordinate system.

Step 3 Registration Procedure

Anesthetize or sedate the patient and anchor his head in the head clamp. With the spark gaps in place on the microscope, focus on each of the fiducials and determine the coordinates of the microphones (Section 5.4.2.1).

Step 4 Focal Plane Determination

Remove the fiducials if necessary and perform the craniotomy. Focus the microscope and calculate the coordinates of the focal, normal and orientation point. Determine the equation of the focal plane and the direction cosines.

Chapter 7 - Error Analysis

This chapter reviews all the major sources of error for the reference - display system. The purpose of such an analysis is to determine the theoretical worst case magnitude of error that could be expected and to see if this error can be tolerated or reduced if found unacceptable. The techniques used to reference the focal plane and CT scans must be determined such that they propagate the least error.

The questions this chapter must answer are: What techniques should be used and what parameters should be optimized to obtain a maximum error preferably less than or equal to 1 millimeter?

The purpose of the reference system is to determine the location of the focal plane with respect to the CT coordinate system. There are four main sources of error for the reference system: 1) error in the slant range distances from the digitizer (7.1), 2) error in focusing the microscope (7.2), 3) CT scan and display error (7.3), and 4) propagation or computation error (7.4). Miscellaneous errors are discussed in section 7.5. The limits on each of these errors will be determined in each section, and the total error evaluated in section 7.6.

7.1 Digitizer Error

The errors in determining the slant range distances can be categorized as either errors in accuracy or precision. According to S.A.C., the accuracy of the slant range is within $\pm 0.1\%$ (bias error) of the measured distance and the precision (repeatability) is within ± 0.01 centimeters.

The parameters that affect the speed of sound in air, and, therefore, the bias error were discussed in Chapter 5. The three major factors are: temperature variations (ΔT), relative humidity (ϕ) and air motions represented by m. Temperature variations and relative humidity cannot be easily controlled, but air disturbances that will distort the sonic wavefront and alter the digitizer reading can be minimized by not opening the operating room door while digitizing, etc. The following equation describes this relationship:

$$\vec{e}_a(d, \Delta T, \phi, m) = k(\Delta T, \phi, m)d$$

where $\vec{e}_a$ is the slant range distance vector error (in cm.) due to the accuracy limitations of the digitizer, k is the bias error percentage (worst case $\pm 0.1\%$), and d is the slant range distance (in cm.). $\vec{e}_a$ is represented as a vector because this error acts along the line between the spark gap and microphone.

Based on the fundamental analysis of Chapter 5, the speed of sound is affected most by temperature variations. If the bias error percentage, k, given by S.A.C., is based only on temperature, a temperature variation, ΔT, of $0.6^{\circ}C$ corresponds to a k of $\pm 0.1\%$. Temperature differences from the operating room ceiling to the operating table were measured during a typical surgical procedure and the mean ΔT was experimentally found to be $0.2^{\circ}C$. Since k is a linear function of the temperature variation, experimentally k = $\pm 0.034\%$ for the operating room environment. The discrepancy between our experimental value of k and the worst case value of 0.1% indicates that the operating room is a well controlled atmosphere for the operation of the digitizer and may produce smaller errors than assumed by S.A.C.

The slant range distance error in precision is a function of the digitizer's clock cycle frequency and is fixed at ± 0.01 centimeters.

$$\vec{e}_p = 0.01 \text{ cm.},$$

where $\vec{e}_p$ is the precision slant range distance error.

The worst case slant range distance error for each spark gap - microphone path ($\vec{e}_d$ in cm.) can be expressed as the sum of the worst case errors in accuracy and precision:

$$\begin{aligned} \vec{e}_d &= k(\Delta T, \phi, m)d + \vec{e}_p, \\ &= 0.1\%d + 0.01 \text{ cm.} \end{aligned}$$

The worst case digitizer error ($\vec{e}_d$), again, is a vector because it acts along the line between the spark gap and microphone. Its impact on the magnitude of the total digitizer error (e_{td}), therefore, depends on the direction of the spark gap - microphone line. An estimate of this worst case error for three slant ranges acting at typical angles is

$$e_{td} \cong 2(0.1\%d + 0.01) \text{ cm.}$$

Reducing d will reduce e_{td}.

One technique to reduce digitizer errors due to random disturbances, such as air motions, is to average multiple samples. Since the digitizer can determine approximately 30 slant range distances per second (transmitting data at 9600 baud), averaging several seconds of data could reduce the error that would result with one sample by a factor of 1/ n, where n is the number of samples for a normal distribution. [18] This technique is explained in the software of Chapter 9.

7.2 Focusing Error

There will be a certain amount of error in focusing the microscope, partly due to optical limitations and partly due to human error. A quantitative description of the microscope's optical properties were presented in Table 2.1.

There are two types of focusing error: errors in depth of field and transverse error in the focal plane. The larger error normally comes from the depth of field. From Table 2.1 it is observed that an increase in magnification results in a decrease in depth of field. The smaller the depth of field, the smaller the focusing error. Therefore, the highest magnification should be used when registering the microscope.

At the highest magnification (microscope scale factor 2.5) the depth of field is two millimeters and the optical field size is 1.45 centimeters. The transverse error is determined by the ability to focus non-intersecting crosshairs on the focal point within the focal plane. At the highest magnification the distance between the crosshairs is approximately one millimeter. See Figure 7.1. At best, an untrained observer can focus the microscope within a volume of a cylinder with a transverse diameter of one millimeter and a height (depth of field) of two millimeters. The surgeon, however, can probably reduce this error through experience with the microscope to be within one millimeter in all directions.

Two other factors affect the focusing error - parallax error and microscope balancing. Since the crosshairs are in only one ocular, there will be a small amount of parallax error in the visual interpretation of the focal point. If the microscope is not balanced properly in all planes, it

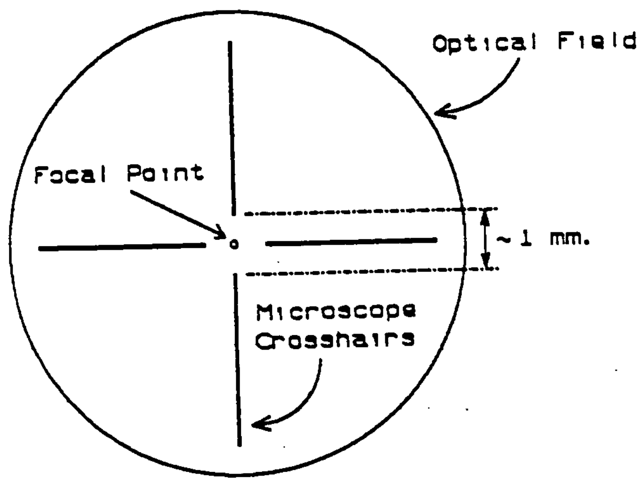


Figure 7.1 - Microscope Crosshairs

will be difficult to focus on a specific point because the microscope will drift after the locking mechanism is engaged.

The focusing error is, therefore, a function of microscope magnification (depth of field), surgeon experience with the microscope, parallax error and errors due to an improperly balanced microscope.

Based on an estimate of the above errors, the worst case focusing error is on the order of one millimeter with a properly balanced microscope and an experienced surgeon.

$$\vec{e}_f = 1.0 \text{ mm},$$

where $\vec{e}_f$ is the worst case focusing error written as a vector because it can act in any direction.

7.3 CT Scan/Display Error

Error can also result from the CT scanning procedure, the fiducial composition, size, shape and placement and the reconstruction/display calculations and procedure. These sources of error are described in this section.

7.3.1 CT Resolution

The head CT scanning field covers a 25 x 20 centimeter rectangular area and, since the scanner resolution is 320 x 320 voxels, the measured resolution in the center of the scan in the x-direction is 200mm/320voxels or 0.6 mm/voxel and in the y-direction 250mm/320voxels or 0.8 mm/voxel. The minimum voxel size in the z-direction (body axis) is the minimum slice thickness, 1.5 mm. Unfortunately, practical constraints on the use of the CT scanner prevent such step-by-step scanning at 1.5 millimeters per slice. A maximum of 20 slices are usually taken at least 5 mm thick with no overlap, so the voxel z dimension is typically 5 mm. The worst case CT resolution error occurs when a fiducial is calculated to be at the center of a voxel and it is actually at one end.

$$|\vec{e}_r| = \sqrt{(0.6\text{mm}/2)^2 + (0.8\text{mm}/2)^2 + (5\text{mm}/2)^2} = 2.5 \text{ mm.}$$

This vector error, from a worst case point of view, prevents the specification of total system error less than 1

millimeter, but it can be reduced as explained in the next section.

7.3.2 Fiducial Error

Since the CT detectable fiducials will link the microscope position to the CT scans, they can also contribute to the error of the reference system. Their careful design is, therefore, important and will be discussed in this section.

7.3.2.1 Fiducial Composition, Size, and Shape

There are several constraints on the fiducials that will determine their composition and size, their ability to be CT scanned and, therefore, the error that they will impose on the reference system. Since a CT slice is actually a density map, the fiducial composition must be dense enough to appear clearly in the CT scans. Metals meet the density criteria, but their repetitive molecular structure causes x-ray scattering that distorts the CT scan. However, amorphous materials with irregular molecular structures such as glass will not cause scattering and they can be doped with lead to increase the density. Glass beads of 2 and 5 millimeters in diameter were CT scanned, but only the 5 millimeter sample was clearly seen. Glass appears to be a suitable fiducial material.

The shape and size of the fiducial is important for two reasons. It must not be large and uncomfortable since it might be attached to the patient's head for up to twenty four hours. It also must be large enough to be visible to the surgeon, as well as small enough to define a unique point in the CT scans.

Since the thinnest practical CT slices are 0.5 centimeters thick, any fiducial smaller than that could be detected in the scan, but its position within the slice would be unknown. The shape of the fiducial must be irregular to overcome this problem without resorting to an uncomfortable 0.5 centimeter diameter glass bead. Two different designs are proposed:

1) a glass wedge whose CT scan density would vary depending on the position of the slice. See Figure 7.2.

2) a glass "N"-shape that is used with the stereotactic frame and defines the scan position by the distance between the elliptic intersection of the CT slice and the fiducial. See Figure 7.3.

Since the glass wedge would be difficult to make precisely, the "N"-shaped glass fiducial was chosen to be made approximately 2 centimeters square out of 2 millimeter diameter glass rod. The "N" must be oriented such that the CT scan intersects both the parallel posts and the crosspiece. Initial work, however, will be conducted with

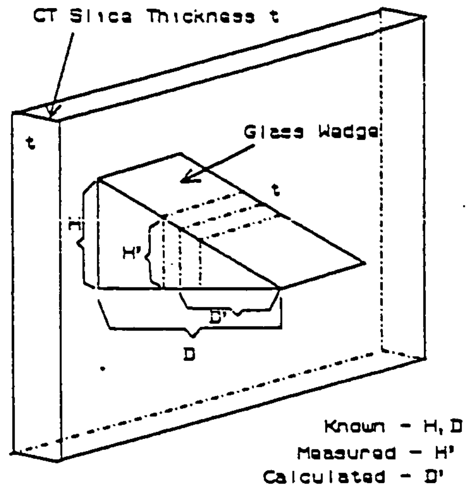


Figure 7.2 - Glass Wedge Fiducial

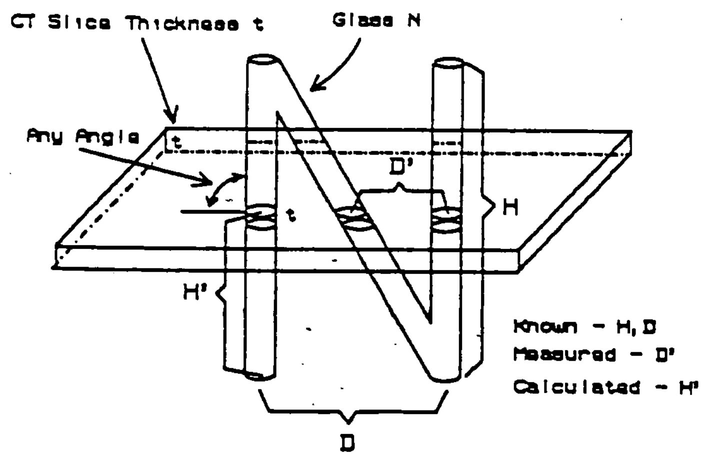


Figure 7.3 - N Shaped Fiducial

the 5 millimeter glass beads; and the construction of an "N" shaped fiducial left for future work.

7.3.2.2 Fiducial Placement

The spatial distribution of the required three fiducials, like that for the spark gaps, is important in reducing error. The spatial distribution contributing the least error would be to place the fiducials at the vertices of an equilateral triangle (see Section 5.4) [8]. Since it might be uncomfortable to attach three fiducials in such an orientation on the patient's head, the proposed sites would be the temples and forehead.

7.3.2.3 Total Fiducial Error

The ability of the fiducials to define the CT coordinate system based on CT scans and register the position of the microscope based on their visibility is primarily a function of two variables, as indicated below:

$$\vec{e}_{fid}(\vec{e}_f, \vec{e}_r)$$

where $\vec{e}_{fid}$ is the vector error due to the fiducials, $\vec{e}_f$ is the focusing error, and $\vec{e}_r$ is the CT resolution error. Since the "N"-shaped fiducial will determine the center of the 0.5 centimeter CT slice, the CT resolution is also a function of the fiducial shape and is, therefore, much less than the worst case value of 5.1 millimeters given in Section 7.3.1. The worst case fiducial error must be

determined experimentally before a quantitative value can be assigned, and will be left as future work.

7.3.3 Display/Reconstruction Error

There is one major source of error that comes under this category - errors due to reconstructing or interpolating the CT slice ($\vec{e}_i$) or contour. It is based on the number of CT slices (n_s), the slice separation (sep), the angle between the reconstructed slice and the serial slices (θ) (hence, the number of points common to both the reconstructed and serial CT slices) and the type of interpolating algorithm used (A).

The most important factor in interpolation is the number of data points - the more points the smoother and more accurate the reconstructed curve. The number of data points depends on the slice separation and the number of slices. Therefore, the error between a CT image reconstructed from many CT scans and a CT slice produced by the CT scanner directly can be represented as:

$$\vec{e}_i(A,\ \theta(n_s, \text{sep})),$$

where $\vec{e}_i$ is the interpolation error. Again, the effect of this error must be determined experimentally and will be left as future work.

7.4 Computation Error

The errors due to digitizer calculations, focusing, and CT scan reconstruction and display can be magnified as they propagate through the calculations necessary to reference the focal plane and CT scans. The effect of this propagation depends on the calculations performed and the orientation of the vector errors, and will be discussed in detail in Chapter 9. This error will be referred to as ϵ_{comp}.

7.5 Miscellaneous Errors

There are three smaller and probably negligible sources of error that should be mentioned. 1) There is a possibility that the operating table is disturbed after the registration procedure, which will relocate the position of the CT scans with respect to the digitizer microphones and contribute to the error of the reference system. 2) Since the fiducials will be attached to the patient's skin, there may be some relative skin - brain motion between CT scanning and the registration procedure. 3) There may be computation error in transforming the coordinates of the reconstructed scan to the microscope coordinate system, which would result in some display error without careful programming using floating point arithmatic.

7.6 Conclusions

The main purpose of this chapter was to determine the sources of error for the reference - display system and determine the values of certain parameters to produce the least amount of error.

Although the probability of a worst case error situation occuring is small, an analysis of this type was performed instead of a statistical analysis to simplify the calculations and get a general idea of the feasibility of the reference - display system. The design specification is that the total system error must be less than or equal to 1.0 millimeters. This analysis indicates that there is only one adjustable parameter, the microphone - spark gap distance, which is actually not that adjustable given the operating room constraints.

The computation error ($\vec{e}_{comp}$) is a function of the digitizer error ($\vec{e}_d$), focusing error ($\vec{e}_f$), and, most importantly, the algorithms used to reference the system. As mentioned in section 7.4, this error can propagate through the various registration steps and calculations. Therefore, to determine this error, the reference algorithms must be written and evaluated then adjusted appropriately. This work is described in Chapter 9.

Finally, the error due to interpolation ($\vec{e}_i$) will be estimated and adjusted based on the CT scan reconstruction procedure not covered in this thesis.

Unfortunately, since the CT scan resolution, focusing error and fiducial error cannot be improved by adjusting available parameters and the magnitude of $\vec{e}_f$ is at least one millimeter, the total worst case error cannot be less than or equal to one millimeter.

Since these errors can act in different directions and this is a worst case analysis, the concept of developing a practical system has not been disproven.

Chapter 3 - Spark Gap Multiplexer Design

Since three spark gaps are needed to determine three points on the microscope and, therefore, its position in space, and the digitizer we purchased has only one spark line, a device is needed to switch the single input spark line to the three spark gaps. Science Accessories sells a multiplexer that can switch up to eight spark gaps for $3,500, but since only three sparks gaps need to be switched and the switching rate can be slow, it was less expensive to design our own three spark gap multiplexer. This chapter describes the specifications, constraints and problems associated with the building and design of the multiplexer.

3.1 Design Specifications/Constraints

The design specifications/constraints were to build a switching circuit that could direct the incoming spark gap signal from the digitizer to one of three user selected spark gaps. More specifically: 1) The switching circuit must handle the 350 volt spark signal and not allow it to arc within the switch. 2) The circuit must be properly shielded to prevent inductive interference with the IBM PC and the digitizer. 3) The control circuit must allow both manual and computer control of the selected spark gaps. 4) The final cost must be less than $3,500, including labor for development.

8.2 Circuit Description

The circuit can be divided into five parts: control circuitry, switching circuitry, display circuitry, power supply circuitry and shielding considerations. Refer to Appendix 5 for schematics and circuit layouts.

8.2.1 Control Circuit

In order to make the multiplexer computer or manually controlled, a four pole-double throw toggle switch was mounted on the front panel. In manual mode, the user can select the appropriate spark gap by two toggle switches which turn on and off two 5 volt lines (TTL logic). In computer mode, the input to the control circuitry is the 5 volt TTL parallel port output from the IBM sent to the circuit by a back panel mounted DB-25 connector. The switch select inputs are processed by a 74139 2-4 channel decoder which outputs three high signals and one low signal for the unique two bit input signal. Since three spark gaps are used only three of the four decoder outputs are connected. This signal is then inverted by a 7406 open collector quad inverter so that the switch selected is high and the others are low [47]. This signal then goes to the power transistors.

A back panel mounted jack, switched on and off by a PRMA 1A05 reed relay and controlled by the IBM parallel port, was added for accessories.

8.2.2 Switching Circuit

The main part of the switching circuit are the single pole-single throw mercury wetted reed relays R1, R2, and R3. A 5 volt, 91 milliamp signal is needed to close the normally open switch. Mercury wetted relays were purchased that have a dielectric breakdown greater than 1000 volts dc so the signal will not arc in either of the two open switches. Mercury wetted reed relays are position sensitive so they had to be mounted vertically. Diodes were placed across each relay control input to prevent possible reverse current surges from damaging the relay and 0.1 microfarad capacitors were placed from 5 volts to ground to reduce power line noise. Since standard TTL control logic does not carry enough current to close the relays, TIP29A power transistor stages were added to draw enough current through the relay when the base signal goes low.

8.2.3 Display Circuit

The display circuitry consists of three 2N3906 bipolar transistors that sense the power transistor collector state and open and close their collector-emitter junction when the base voltage is +5 volts and ground, respectively. When the

circuit closes, the current passes through the appropriate LED indicating the multiplexer status.

8.2.4 Power Supply Circuit

The power supply circuit consists of a modular Polytron 120 volt ac to 5 volt dc, 500 milliamp power supply. A 100 microfarad electrolytic capacitor and a 0.1 microfarad ceramic capacitor were placed between 5 volts and ground to reduce power supply noise. The power supply is protected by a slow blow fuse and has a back panel mounted on-off switch.

8.2.5 Shielding and Grounding

The main problem with designing a switching network to handle a 350 volt spike signal is that the sharp voltage transition induces current in nearby wires causing the digitizer to make false readings or other spark gaps to fire. To eliminate this problem, all connections going into and out of the multiplexer were made with shielded coaxial cable whose integrity was internally maintained by coax connections and copper ground plane switch circuitry. The switch board was separate from the control and power circuit boards for further isolation.

To prevent ground loops internally and between the digitizer and multiplexer all circuit components were soldered point-to-point with a common ground connection. See Figures 8.1, 8.2, and 8.3.

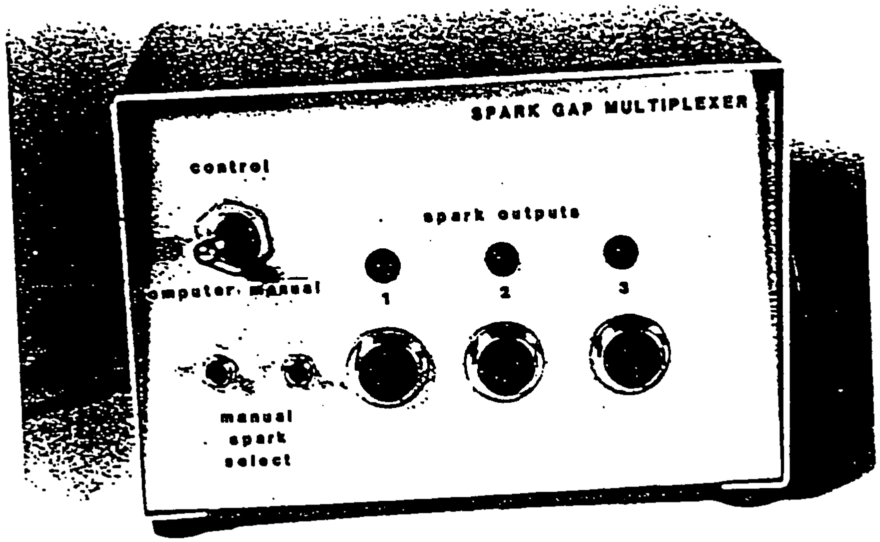


Figure 8.1 - Multiplexer - Front View

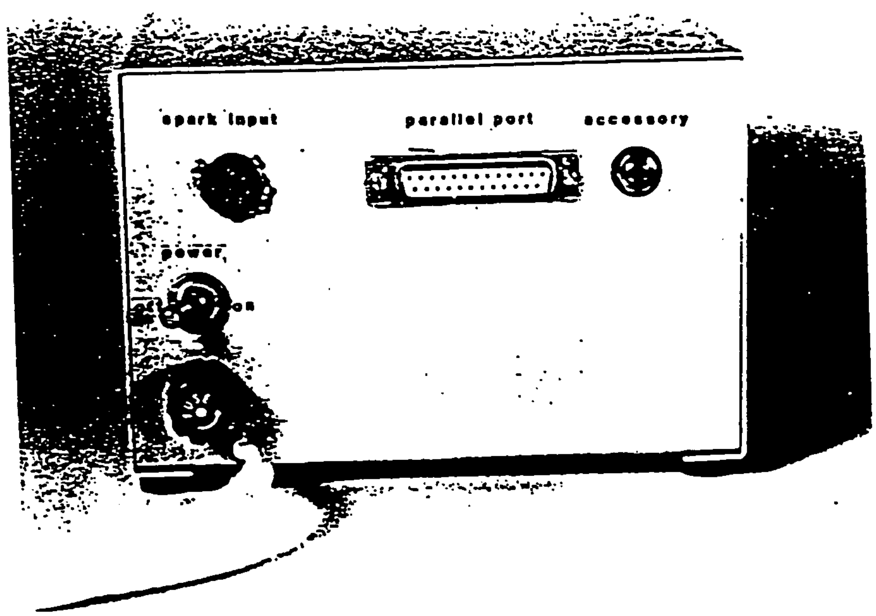


Figure 8.2 - Multiplexer - Back View

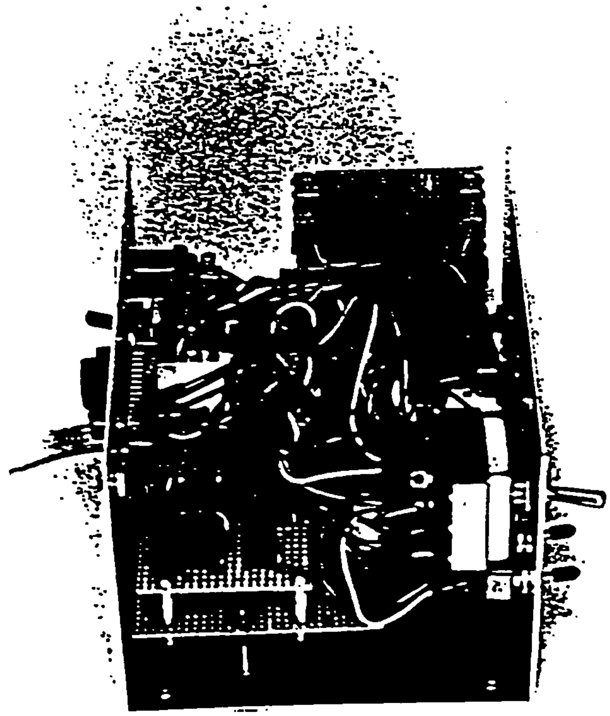


Figure 8.3 - Multiplexer - Top View

Chapter 9 - Software and Computation Error

This chapter describes the software written in BASIC for the IBM PC XT with the 8087 coprocessor (sections 9.1 - 9.4) and includes a quantitative error analysis for each step in the reference procedure (section 9.5 - 9.6).

The software is divided into two files. File FPL performs the steps in section 6.4.1 and establishes the relationship between the relative position of the spark gaps and the focal plane by calculating the oblique spark gap coordinates of the focal (6.4.1.1), normal (6.4.1.2) and orientation (6.4.1.3) points. This program needs to be run once for each spark gap bracket (sitting or supine) and only occasionally thereafter to reestablish the spark gap focal plane relationship.

File REG performs the steps in sections 6.4.2 and 6.4.3, and is run for each operation in the operating room once the CT coordinates of the fiducials have been determined by the CT scanner/computer. The first step is the registration procedure (6.4.2) to calculate the CT coordinates of the microphones by focusing on each fiducial. The second step (6.4.3) calculates the equation of the focal plane, the coordinates of the focal point and the three direction cosines of the Y_M microscope axis in CT coordinates for each microscope position. The software and documentation are in Appendix C.

9.1 Digitizer Control

The subroutine SRINP, used by both files FPL and REG, was written to control the digitizer and the spark gap multiplexer and to store the distances in an array. The first part writes a binary code (00, 01, or 10) to the parallel port (address 3BC hex) on the IBM monochrome adapter card which sends a signal to the spark gap multiplexer and sets the appropriate relay. Then the RS-232 serial port of the IBM is opened to receive the slant range data from the digitizer. This data is sent as a 26 character string as shown below.

11111S22222S33333S44444CRLF

1, 2, 3 and 4 represent the five digit metric slant range distances for each microphone, S represents a space character, and CRLF is a carriage return and line feed. The string is searched until an ASCII line feed character is found marking the end of a set of four slant ranges. The next 26 character string is from the digitizer's "last sample" buffer and is ignored. The data is then received 26 characters at a time until the desired number of samples has been obtained. Then decimal points are inserted to read the slant ranges in centimeters (XXX.XX) and then stored in array SLANT. While the data is received, the IBM

communications input buffer is monitored, interrupting and resuming the data flow depending on available buffer space.

Since the operating room equipment and patient are generally in two different setups (depending on the craniotomy site) blocking a different microphone each time, this subroutine throws out the slant range data from the blocked microphone, which is determined when the user identifies the procedure (left temporal or right frontal craniotomy). The IBM serial port is then closed by writing a binary code (1010) to the port's address (3FC hex) disabling digitizer communication and turning off the spark gaps. The means and standard deviations of the slant ranges are then calculated. If the data from any microphone has more than five bad data points (distances ≥ 250 centimeters, indicating the signal was blocked or never received) or the standard deviations are found to be greater than a predetermined limit (SDLIMIT) set in the software (presently set at 0.05 cm.), the subroutine will prompt the user to try again.

After the mean slant ranges are stored in array SRMEAN, the spark gap multiplexer switches to the next spark gap and repeats the process until all three spark gaps have been fired.

9.2 Spark Gap - Focal Plane Relationship

This section discusses the subroutine FPLANE (in file FPL), which executes the procedure described in Section 6.4.1 and calculates the oblique spark gap coordinates of the focal, normal and orientation points for the sitting or supine spark gap brackets. File FPL requests the type of spark gap bracket, sitting or supine, and sets FFLAG such that the oblique coordinates are stored in the proper file.

The user is then instructed to anchor the fourth spark gap under the microphones, being careful not to block the spark gap - microphone line of sight with the microscope. SFLAG is then set to indicate to subroutine SRINP that only one spark gap should be fired. SRINP is called and the square of the slant range distances from the fourth spark gap are stored in array DIST. The user is then asked to focus on the tip of the fourth spark gap and call SRINP, firing the three spark gaps on the microscope. The oblique spark gap coordinates of the three microphones are then calculated by following Equations 6.3, 6.4, 6.8, 6.9, and 6.12. Once these are determined and stored in array FX, subroutine NEWTON is called with NFLAG equal to one, indicating that the cosine of the angle w (Equation 6.1) will be represented by CW.

NEWTON, with NFLAG equal to one, specifically solves three nonlinear equations determined by the oblique distance

formula (Equation 6.13) [10]. Preset negative initial values are used since the z coordinate of the focal point is negative and positive initial values could cause the solutions to converge to a geometrically valid mirror result above the x-y plane. Newton's method solves equations in the form $F_i(x) = 0$ where $F_i(x)$ is the vector of i equations. The solution vector X_i can be found by calculating:

$$X_i^{(k)} = X_i^{(k-1)} - J_i(X_i^{(k-1)})^{-1} F_i(X_i^{(k-1)}) \quad (9.1)$$

where k is the iteration number ($X_i^{(1)}$ are the initial values), and $J_i(X_i^{(k-1)})$ is the Jacobian matrix of partial derivatives of each equation i with respect to the unknowns X_i evaluated at $X_i^{(k-1)}$ [10]. Since i = 1 to 3, the Jacobian matrix is 3x3:

$$J(X) = \begin{vmatrix} \frac{\partial F_1(X)}{\partial X_1} & \frac{\partial F_1(X)}{\partial X_2} & \frac{\partial F_1(X)}{\partial X_3} \\ \frac{\partial F_2(X)}{\partial X_1} & \frac{\partial F_2(X)}{\partial X_2} & \frac{\partial F_2(X)}{\partial X_3} \\ \frac{\partial F_3(X)}{\partial X_1} & \frac{\partial F_3(X)}{\partial X_2} & \frac{\partial F_3(X)}{\partial X_3} \end{vmatrix}$$

NEWTON calculates the Jacobian matrix and calls subroutine INVERSE which inverts the Jacobian matrix. Equation 9.1 is then solved for each iteration, k, until either 30 iterations are reached or until;

$$(X_i^{(k)}-X_i^{(k-1)})/X_i^{(k)} \leq TOL$$

where TOL is a set tolerance value of 0.001 centimeter. The user is notified if the solutions have not converged in less than 30 iterations.

Subroutine INVERSE uses the Crout algorithm (a variation of the standard Gaussian Elimination technique only with maximal pivoting strategies) to invert the 3x3 Jacobian matrix [10]. The elements of the inverted matrix are solutions to the equations:

$$J_i J_i^{-1} = I$$

where I is the 3x3 identity matrix.

The solutions to Equation 9.1 can be calculated directly by Gaussian Elimination by letting $Z = J_i^{-1} F_i$ and, therefore, $J_i Z = F_i$ and then solving for Z.

At this point, the solutions to Equation 6.13, the oblique spark gap coordinates of the focal point, are stored in array FOCAL and section 6.4.1.1 is complete.

After solving for the focal point, FPLANE instructs the user to focus the microscope on Points 1, 2 and 3 of a fixed grid coordinate system with the crosshairs of a small protractor device at the origin. This is to establish a fixed coordinate system such that the fixed coordinates of the microphones can be determined. See Figure 9.1.

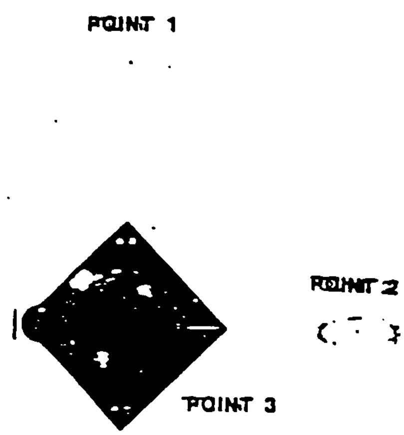


Figure 9.1 - Grid Coordinate System

When focusing on Point 3, the user is asked to align the microscope crosshairs with the protractor crosshairs and focus as normal to the protractor as possible. Then the user is instructed to move the microscope away from the protractor by turning only the focusing knob of the microscope. The slant range distances for each of these points is stored in array SDATA.

Subroutine DISTANCE converts the slant range data for Points 1, 2 and 3, in SDATA, into the oblique spark gap coordinates of the three microphones (Equations 6.8, 6.9 and 6.12) and calculates the distances between the microphones and focal points (Points 1, 2 and 3) by the oblique distance

formula (Equation 6.14). The fixed coordinates of the three microphones are then determined by solving three sets of three simultaneous nonlinear equations (Equation 6.15). Then NFLAG is set to zero to let cos(w)=0 and allow subroutine NEWTON to solve the three sets (one for each microphone) of three nonlinear equations (Equation 6.15).

At this point, we know the fixed coordinates of each microphone relative to the grid coordinate system. These coordinates are stored in array MIKE.

The next step is to calculate the fixed coordinates of the normal point (6.4.1.2) based on the slant range data in SDATA. Subroutine DISTANCE is called again and the distances between the microphones and normal point are calculated and stored in array DIST. NEWTON is called again with NFLAG equal to zero and solves the three nonlinear equations of Equation 6.16 for the fixed coordinates of the normal point.

The oblique spark gap coordinates of the normal point are then calculated by first determining the normal point - microphone distances by applying the standard Cartesian distance formula of Equation 6.15. NEWTON is then called again (NFLAG=1) to solve Equation 6.17 for the oblique spark gap coordinates of the normal point. These oblique coordinates are then added to array FOCAL.

The next step is to follow the procedure of section 6.4.1.3 and calculate the oblique spark gap coordinates of

the orientation point. The first step is to calculate the coefficients of the focal plane at Point 3 of the grid coordinate system by solving Equation 6.21. Once the focal plane is known, Point 1 is projected onto the focal plane and the fixed coordinates of the orientation point is determined by Equations 6.23, 6.24, 6.25 and 6.26. The distances between the orientation point and the microphones are then determined by applying Equation 6.15 and the oblique spark gap coordinates of the orientation point - calculated by calling subroutine NEWTON (NFLAG=1) to solve Equation 6.27. The oblique coordinates are then stored in array FOCAL.

The oblique spark gap coordinates of the focal, normal and orientation points are then transferred from FOCAL and stored in files SIT or SUP depending on the spark gap position and surgical procedure.

9.3 Registration Procedure

File REG is the driver for the registration procedure and focal plane determination. Once the patient's head has been fixed in the head clamp, the surgeon is asked to indicate which type of procedure will be performed, left temporal craniotomy or right frontal craniotomy (see Section 2.1). This will indicate which of the four microphones (slant range values) will not be used. Should another, less common, operational setup be required, the microphone that

will not be used can be indicated in the software prior to the procedure by changing MNOT. The surgeon is also asked the position of the patient for the procedure (sitting or supine), which will determine the appropriate spark gap bracket (see Chapter 10) and, therefore, relative positions of the spark gaps and microscope. Depending on the position, file SIT or SUP will be read and the oblique spark gap coordinates of the focal, normal and orientation points stored in array FOCAL.

Subroutine REGISTER is called and the surgeon is then instructed to focus on each of the three fiducials, pausing between each one for SRINP to fire the spark gaps and determine the slant range distances. REGISTER then asks the surgeon to enter the CT coordinates of each fiducial. Subroutine DISTANCE determines the distances from the microphones to the fiducials and NEWTON solves the three sets of simultaneous nonlinear equations for the coordinates of the microphones in CT coordinates and stores the data in array MIKE (Equation 6.15).

The CT coordinates of the array MIKE are then written to file MIKE. Therefore, if the IBM fails, the registration procedure need not be repeated. The user is asked at the beginning of the procedure whether or not the computer failed after the registration procedure. The microphone coordinates are then recalled, if necessary, and the registration procedure is skipped.

9.4 Focal Plane Determination

With the microphone coordinates determined in CT coordinates, the surgeon is then instructed to remove the fiducials, if necessary, and continue with preparing the operative site and perform the craniotomy. If the craniotomy site has not been determined, the reference - display system can be used to reconstruct and display images that might be useful in planning where to "open". REG then calls subroutine SLICE, which instructs the surgeon to indicate when the microscope is focused so SRINP will be called to fire the spark gaps.

The CT coordinates of the focal, normal and orientation points are then determined by subroutines DISTANCE and NEWTON, which specifically solves Equation 6.28 as explained in Section 6.4.2.2. The equation of the focal plane is determined by Equation 6.21 and the direction cosines calculated by Equations 6.30, 6.31 and 6.32. The focal plane coefficients and direction cosines are displayed on the screen along with the coordinates of the focal point. Once communication between the IBM PC and the Treatment Planning Computer has been established, this data will be transmitted directly to the Data General Eclipse for the image reconstruction and display.

9.5 Error Analysis

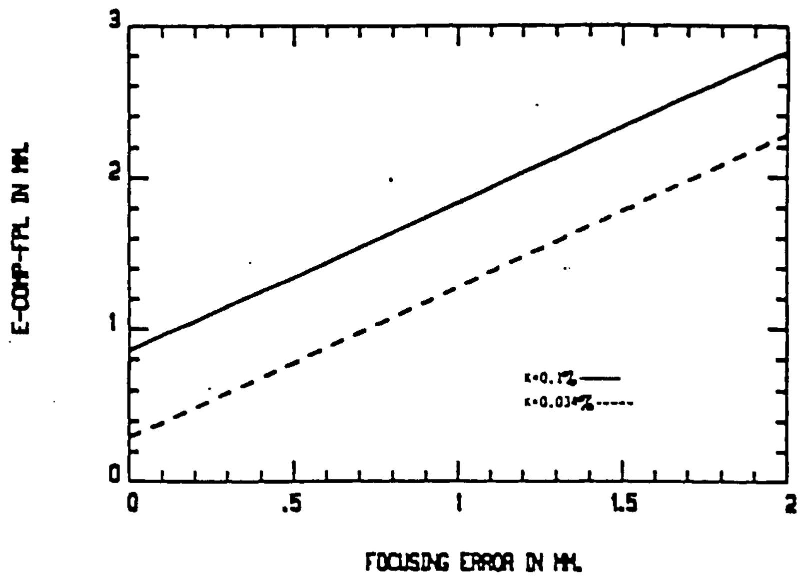
The purpose of this section is to quantitatively determine the error due to the computations (e_{comp}) described in this chapter and outlined in Chapter 7.

9.5.1 FPL Error

The computation error due to establishing the spark gap - microscope relationship with the program FPL ($e_{comp-FPL}$) is a function of the digitizer error, $\vec{e}_d$, and the focusing error, $\vec{e}_f$. This error was evaluated by calculating the oblique spark gap coordinates of the focal point, adding the magnitude of $\vec{e}_d$ to the slant ranges and the magnitude of $\vec{e}_f$ to focal point coordinates and then observing the magnitude of the resulting error as a function of $|\vec{e}_f|$. See Figure 9.2. The solid line is the error when k = +0.1% (worst case bias percentage) and the dashed line is with k = +0.034%, the expected worst case based on operating room temperature variations. It can be seen that with a focusing error of 1 millimeter, $e_{comp-FPL}$ = 1.8 millimeters with a 0.5 millimeter change in $e_{comp-FPL}$ per 0.5 millimeter change in $\vec{e}_f$. This value is a combination of worst case errors for $\vec{e}_f$ and $\vec{e}_d$, but for typical slant range distances stored in file TSLANT.

There is another source of error that should be mentioned. The oblique coordinates of the focal, normal and

FIGURE 9.2 - OBLIQUE FOCAL POINT ERROR

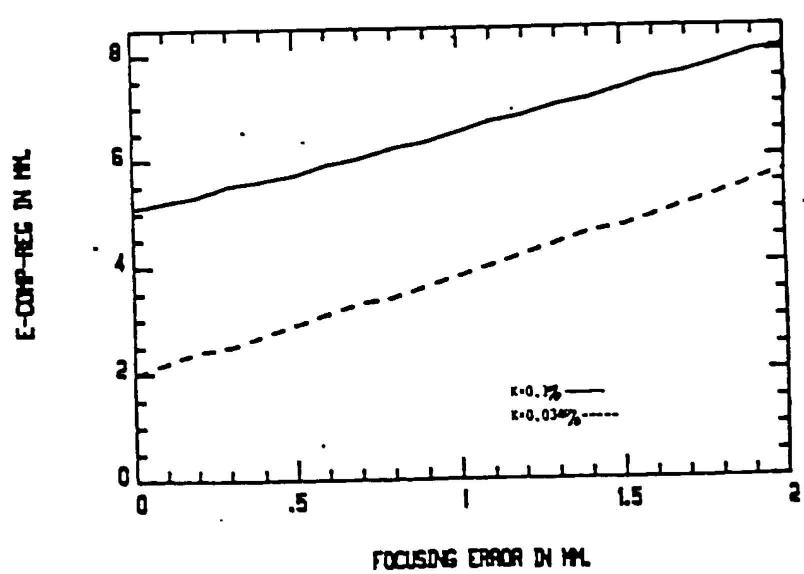


orientation points will be determined prior to the procedure and their accuracy is dependent on the precision of the spark gap holder, which will be removed and then replaced when the microscope is draped. This will introduce another error, $e_{s\text{-}holder}$, which was experimentally determined (see Appendix F) to be 0.9 millimeters and in a worst case analysis can be added to the propagation of the focusing error. This error might be reduced by redesigning the spark gap holder - microscope mount, which may eventually be changed should the procedure in the operating room introduce more physical constraints.

9.5.2 REGISTER Error

The computation error due to the propagation of $e_{comp-FPL}$, $\vec{e}_f$, $\vec{e}_{s-holder}$ and $\vec{e}_d$ through the registration procedure can also be quantitatively determined. Again, the average error in the determination of the microphone coordinates is based on typical slant range data (stored in file TSLANT) and shown in Figure 9.3. This is also shown as a function of the focusing error as this error is amplified by focusing on each fiducial. Again, the solid line represents k = +0.1% and the dashed, k = +0.034%. $e_{comp-REG}$ at $|\vec{e}_f|$ = 1 millimeter is approximately 6.5 millimeters where, in general, a 0.5 millimeter change in $|\vec{e}_f|$ corresponds to a 0.5 millimeter change in $e_{comp-REG}$.

FIGURE 9.3 - REGISTRATION ERROR

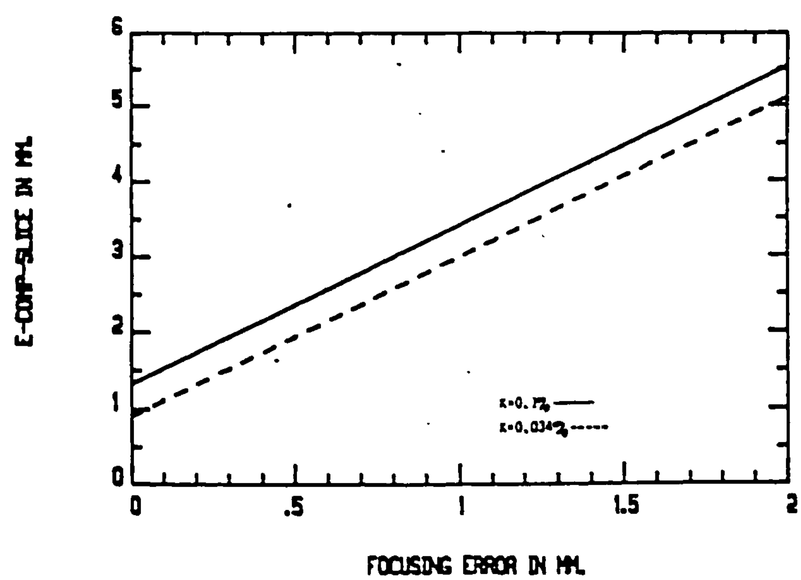


9.5.3 SLICE Error

$e_{comp-SLICE}$ represents the magnitude of errors due to $e_{comp-REG}$, $\vec{e}_d$ and $\vec{e}_f$ as they have propagated through the calculations of the focal point for a typical reconstructed CT image. It is shown in Figure 9.4 as a function of focusing error for k = +0.1% (solid line) and k = +0.034% (dashed line). With $|\vec{e}_f|$ at 1 millimeter, $e_{comp-SLICE}$ = 3.4 millimeters.

It is interesting to note that the magnitude of the final error, $e_{comp-SLICE}$, is less than the sum of $e_{comp-FPL}$ and $e_{comp-REG}$. This is because each of these errors is a vector and acts in specific directions, partially cancelling others out.

FIGURE 9.4 - FOCAL POINT ERROR



9.6 Error Conclusions

This error analysis is a combination of a typical and worst case situation with typical slant range values and worst case error parameters. The total theoretical worst case error for the entire reference - display system is the sum of the propagated error, $e_{comp\text{-}SLICE}$, the fiducial error, $\vec{e}_{fid}$, and the interpolation error, $\vec{e}_i$:

$$E_T = e_{comp\text{-}SLICE} + |\vec{e}_{fid}| + |\vec{e}_i|,$$

$e_{comp\text{-}SLICE}$, for a focusing error of 1 millimeter, is 3.4 millimeters. Therefore,

$$E_T = 3.4 + |\vec{e}_{fid}| + |\vec{e}_i|,$$

which is unacceptable for neurosurgical procedures. From this analysis, the error due to focusing appears to be the most sensitive parameter and unfortunately cannot be easily adjusted.

At this point the total worst case error is greater than the specification of one millimeter. This means that a more statistical approach should be considered to determine the probability of more common situations. However, should this large error prove to be the case experimentally, new algorithms will have to be developed to try to reduce the propagation of fixed errors such as focusing. Attaching three additional spark gaps to the three fiducials might

reduce the focusing error but since the microphone placement is restricted to the operating room ceiling between the air vent and light tracks (see Figure 2.4) the digitizer line of sight constraint might geometrically prevent proper sound transmission. The experimental results will indicate the next step.

Chapter 10 - Mechanical Design

This chapter describes the hardware that required mechanical design and machining. Spark gap holders were designed to mount the spark gaps on the microscope for two different surgical positions. Microphone mounts were also designed to allow quick and simple placement of the microphone array on the operating room ceiling.

10.1 Spark Gap Holder

The specifications for the design of the spark gap holder are: 1) the spark gap separation can be no greater than 30 centimeters to prevent interference with the patient drape and scrub nurse's procedure, 2) the weight of the holder and spark gaps must be less than 2 kilograms, 3) the spark gap holder must mount on the microscope such as not to interfere with the surgical procedure and manipulation of the microscope, 4) there must be a clear line of sight between all three spark gaps and at least three microphones, 5) since the spark gaps and holder will be in the vicinity of the operative field they must withstand aseptic sterilization, and 6) the spark gaps must be easily and precisely connected to the microscope after the drape bag is in place.

The spark gaps are located at the vertices of an equilateral triangle as determined in section 5.4. The

weight specification was met by building the holder out of plexiglas. The spark gap holder attaches easily to the microscope via a male counterpart to the female dovetail notch on the microscope, which was designed for the attachment of a surgical laser. This meets specification 3. See Figure 10.1. In order to meet the line of sight criteria, two different holder arms were designed for the cases where the patient is supine or in a sitting position. The spark gap holder must undergo ethylene oxide gas sterilization because the spark gap tips are made of stainless steel and would oxidize with aqueous sterilization. The precise attachment of the spark gap

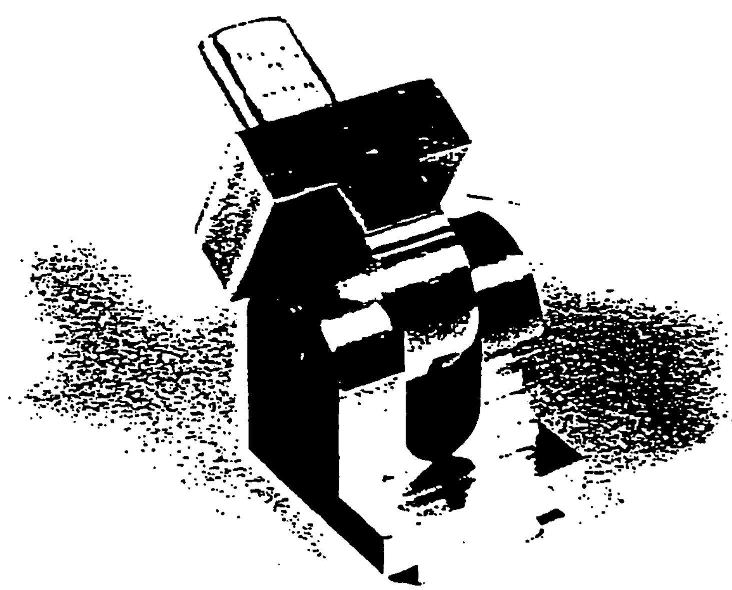


Figure 10.1 - Spark Gap - Microscope Mount

holder to the microscope was done by machining an aluminum "tongue" that attaches to the laser mount and a female slot with two set screws that can precisely relocate the spark gaps to the same position. The microscope drape bag is stretched over the metal tongue until the tongue protrudes, temporarily breaking the sterile barrier. The spark gap holder arm is then slid over the tongue and the set screws are tightened, anchoring the spark gap holder. See Figures 10.2, 10.3 and 10.4.

10.2 Microphone Mounts

The only major specification for the design of the microphone mounts is that the microphones and preamps be ceiling mountable in the operating room within one minute each so the operative procedure is not delayed. The mounts must not be damaged by general operating room preparation and the microphone array must be removable, allowing their use in other operating rooms. Since the exact orientation of the four microphones is not critical, they do not need to be mounted on a rigid framework.

The microphones were attached to a small plexiglas holder that was mounted on the preamp boxes described in section 5.4. The preamp boxes were attached to an aluminum male dovetail section whose female counterpart was mounted on the operating room ceiling between the light tracks and

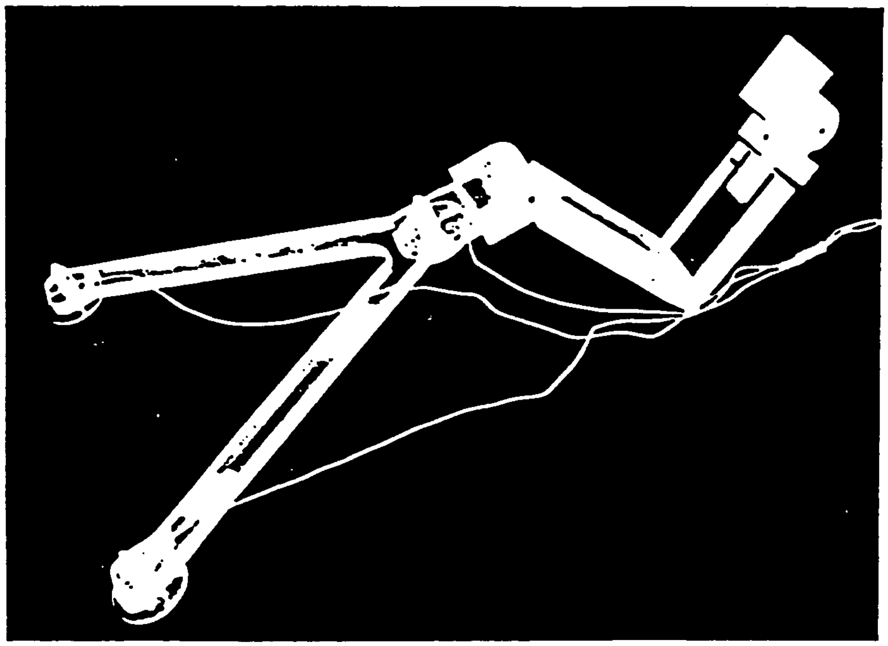


Figure 10.2 - Supine Spark Gap Holder

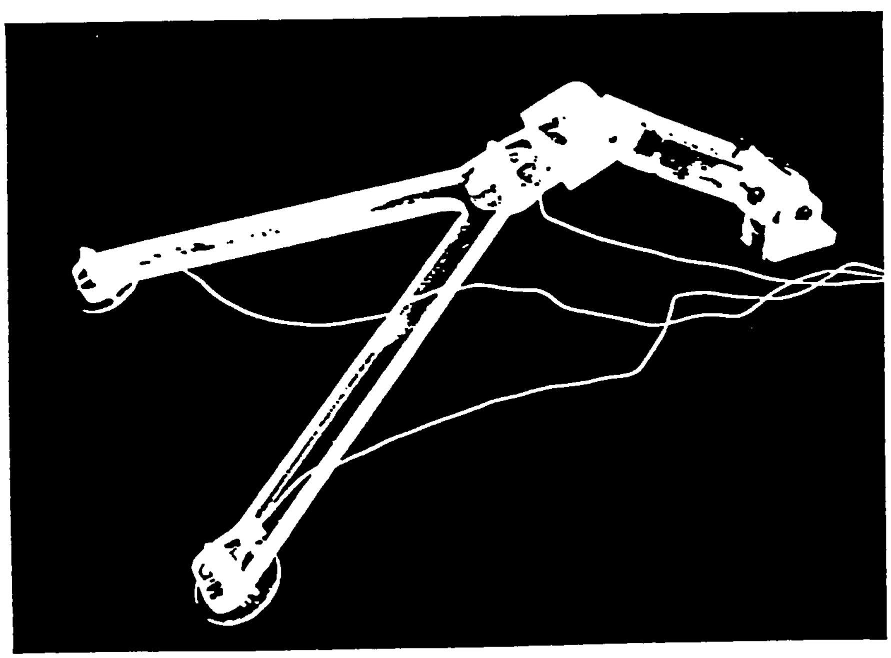


Figure 10.3 - Sitting Spark Gap Holder

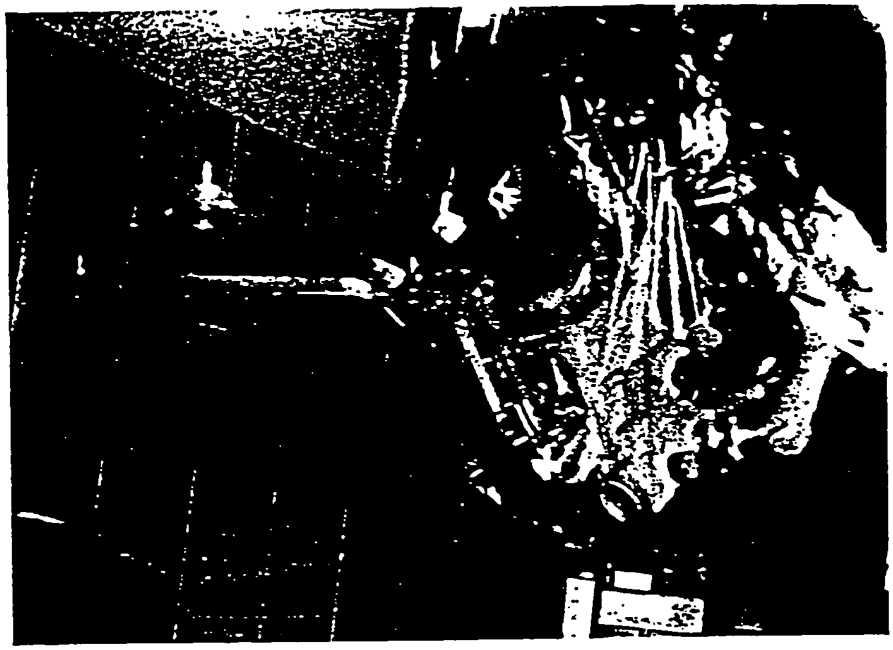


Figure 10.4 - Microscope Mounted Spark Gap Holder

the air vents. A set screw was made to allow the secure positioning of the preamp boxes. The microphones and preamp boxes can be quickly mounted by sliding the dovetail pieces together and turning the set screws. See Figures 10.5 and 10.6. The mechanical drawings for the spark gap holder and microphone mounts are in Appendix D.

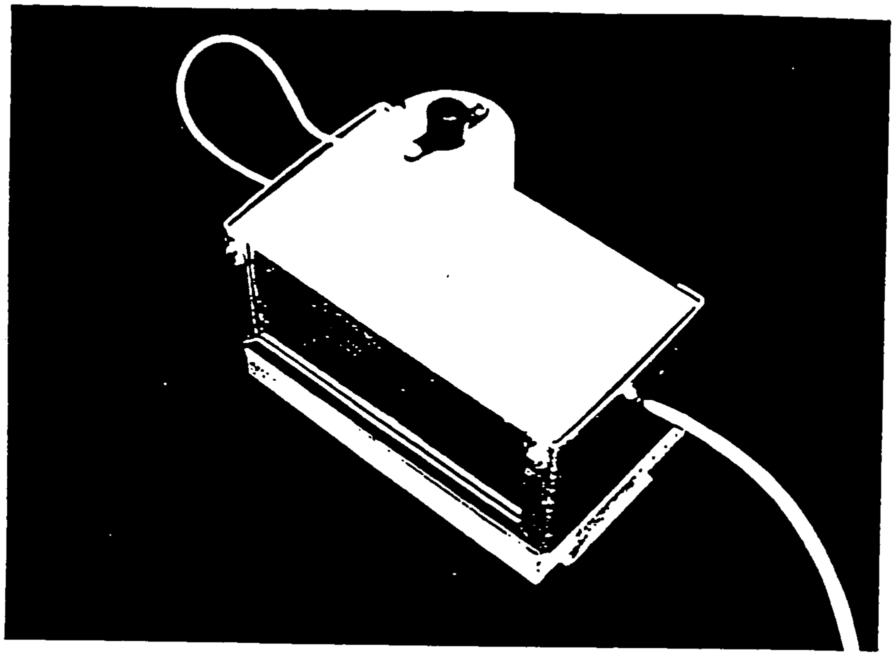


Figure 10.5 - Microphone Mount - View 1

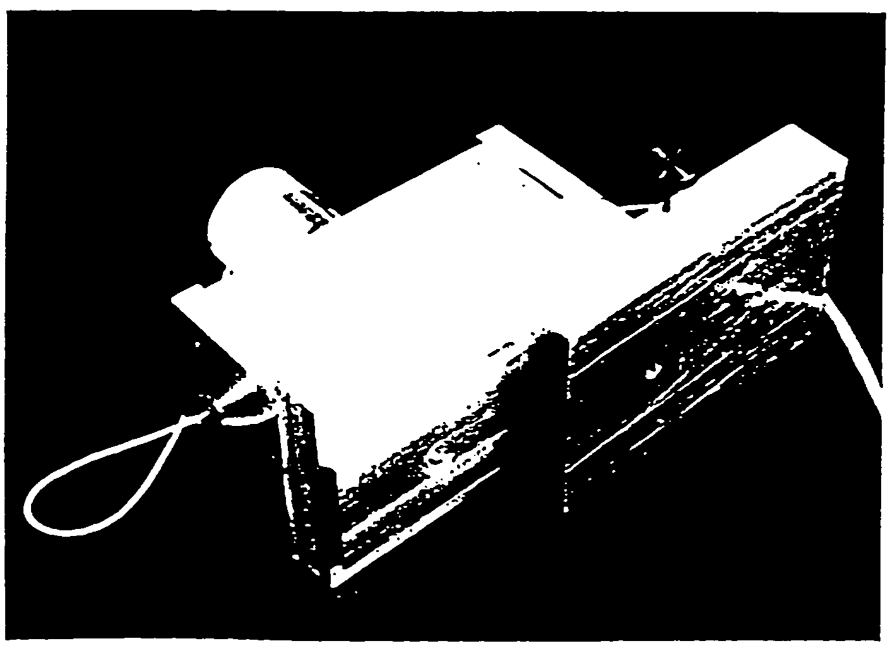


Figure 10.6 - Microphone Mount - View 2

Chapter 11 - System Evaluation

This chapter describes the reference system evaluation including digitizer performance (11.1), phantom design (11.2), error analysis (11.3), experimental results and conclusions (11.4).

11.1 Digitizer Evaluation

The digitizer was tested for accuracy and precision under the following test criteria: 1) single spark gap - microphone separation, 2) spark gap at 0° to the microphone (see Figure 11.1), 3) digitizing rate at 30 points per second, 4) sampling times of three seconds for 50 samples, 5.5 seconds for 100 samples, and 8 seconds for 150 samples, 5) measured spark gap microphone distances were 50 ± 0.1 cm, 100 ± 0.2 cm, 150 ± 0.3 cm, and 200 ± 0.4 cm. The test statistics are in Appendix E. The conclusions from this

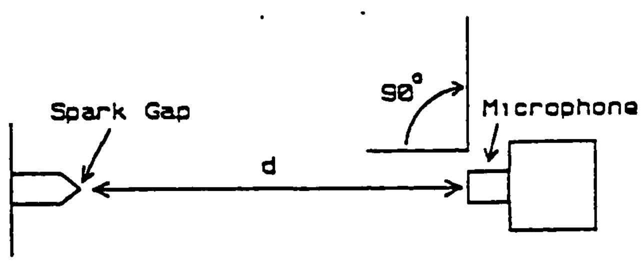


Figure 11.1

Spark Gap - Microphone Orientation

test were that the digitizer meets its specifications for precision, ± 0.01 cm, but it was difficult to determine the results of the accuracy test because we do not have a measuring device that is more accurate than the digitizer itself. The slant ranges do appear to be within ± 0.1% of the measured distance.

11.2 Test Design

In order to determine the accuracy of the reference system, a testing technique had to be developed. Since a goal of this Thesis is to prove that the calculated focal plane is within a specified error (initially 1.0 mm) of the correct focal plane, an evaluation introducing the fewest sources of error is preferred. The error that will result will be easier to trace back to its source.

A block of plexiglas was milled square approximately the size of a human head (18x10x10 cm.) and small points (0.8 mm diameter) were drilled into it with known separations. Three of these points represent fiducials and the other five are test points whose coordinates are known with respect to the coordinate system defined by the fiducials. See Figure 11.2. The coordinates of the fiducial points and test points are given in Table 11.1 below.

Table 11.1 - Test Point Coordinates(mm)

Fiducials

Point	X	Y	Z
1	0.0	0.0	0.0
2	-1.671	7.62	4.854
3	1.016	15.867	-1.75

Test Points

Point	X	Y	Z
1	-4.719	7.62	0.79
2	2.54	0.0	0.0
3	5.949	7.62	4.854
4	6.096	8.247	0.0
5	1.016	15.867	0.226

This test phantom will eliminate the errors related to CT scanning and display/reconstruction. The error determined at the focal point will be the distance between the real and calculated CT coordinates and the only sources of error will be due to slant range, focusing and computation error. A subroutine TEST was written to call the required subroutines and evaluate the focal point error and angular focal plane orientation error. The error at the focal point can be easily determined since the coordinates of the test points are known. The error in the focal plane calculations can be determined qualitatively by refocusing on the grid coordinate system (see Figure 9.1) normal to the x-y plane along the z axis and determining if the focal plane coefficients represent the plane z=0. The x and y direction cosines will indicate angles that add up to 90° if the orientation vector is in the first quadrant of the grid coordinate system.

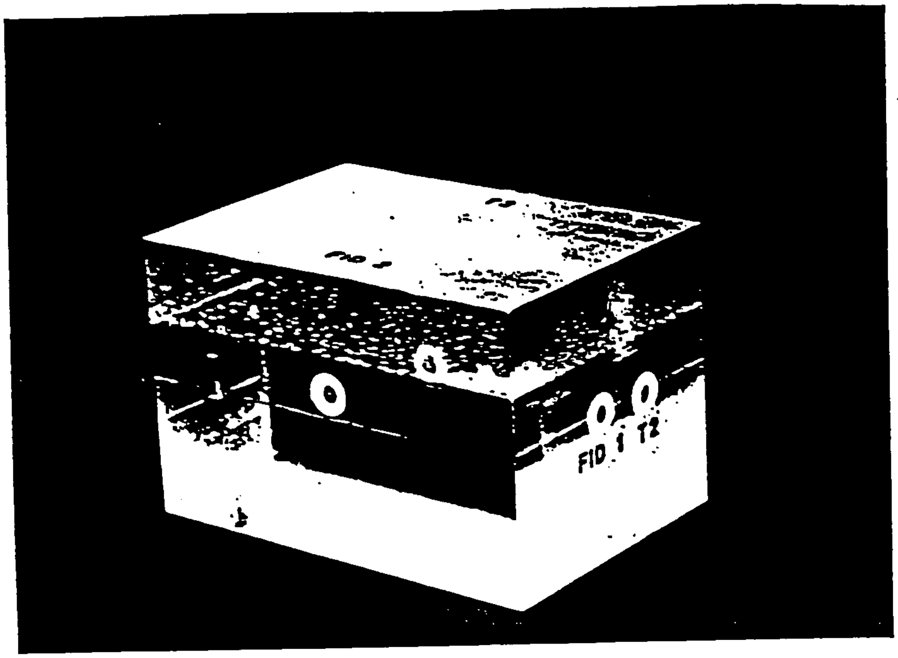


Figure 11.2 - Test Phantom

11.3 Test Error Analysis

This section describes the total worst case focal point error that could be expected by using the test procedure outlined above.

The worst case error for the test phantom is given by:

$$E_{test} = e_{comp-SLICE} + |e_{fid-test}|,$$

where $e_{comp-SLICE}$ is 3.4 millimeters. The fiducial error for the test phantom, $|e_{fid-test}|$, is different than that for the general system. Each test point and fiducial was marked within 0.127 millimeters (0.005 inches), so $|e_{fid-test}|$ is 0.127 millimeters.

$$E_{test} = 3.4 + 0.13 = 3.53 \text{ millimeters}$$

The worst case focal point error is 3.5 millimeters.

The worst case test focal plane error is hard to estimate as the focal plane is defined as four coefficients. It will be analyzed as described in Section 11.2, above.

11.4 Experimental Results

The raw data for the experiments is in Appendix F with a brief description. There are three tests that were conducted to characterize the reference system error: focal point accuracy and precision, resting focal point precision and focal plane accuracy.

The focal point accuracy and precision was determined by first focusing on each of the three fiducials and calculating the coordinates of the microphones in the test phantom coordinate system. The microscope was then focused on each of the various test points on the test phantom multiple times at different angles and the magnitude of the error at the focal point was determined. The average error was 1.1 millimeters, less than the estimated worst case error (11.3), with an average standard deviation of 0.52 millimeters. If the errors due to the fiducials ($\vec{e}_{fid}$) and interpolation ($\vec{e}_i$) also prove to be less than expected, the reference system will have wide range applicability in the operating room. The focal point precision or repeatablity is determined by the standard deviation. If we assume that the magnitude of the focal point error follows a standard

normal distribution, the standard deviation indicates that 68% of the focal point values will be within 0.58 and 1.62 millimeters (one standard deviation), and 95% will be within 0.06 and 2.14 millimeters (two standard deviations).

The resting focal point precision was determined by focusing on the same point and sampling fifteen times to determine the variation in the coordinates due to fixed errors such as air motions, etc. The standard deviations in centimeters of each coordinate were determined and found to be 0.057 (x), 0.066 (y) and 0.055 (z) with values falling evenly on either side of the mean. This indicates that the variations in error values at the focal point could be partially due to a fixed bias error which cannot be removed from the system by changing available parameters.

The focal plane is defined in the CT coordinate system by the four coefficients of the equation of the plane: $Ax + By + Cz = D$. As mentioned earlier in this chapter, by focusing the microscope along the z axis of the CT coordinate system (test phantom) at the origin, normal to the x-y CT plane, the resulting focal plane equation should be approximately $z=0$ ($A=0$, $B=0$, $C=1$, $D=0$). This experiment was conducted by refocusing along the z axis of the grid coordinate system at the origin (Point 3) fifteen times and evaluating the equation of the focal plane. The average values for the plane coefficients were $A=-0.032$, $B=0.106$,

C=1, and D=0.005. This indicates that the focal plane has been determined without any gross error.

A more rigorous test of focal plane accuracy would be to determine the CT (fixed) coordinates of three corners of a large flat surface by focusing on each point. The equation of this plane could then be calculated. Then, by focusing at the center of the surface, the focal plane coefficients could be determined and compared to the surface plane coefficients. This error could then be translated into focal plane error at the edge of the microscope field.

The next step is to evaluate the accuracy of the orientation point coordinates, or specifically the direction cosines indicating the orientation of the focal plane about the optical axis. By focusing the microscope along the z axis at the x-y plane again and keeping the y axis of the microscope coordinate system (Y crosshair in the ocular) in the first quadrant of the grid coordinate system, the sum of the direction cosines should be 1. This corresponds to an angular sum of 90° from the x and y grid axes to the orientation vector. The average angular sum was 90.8° and, again, only indicates that there have not been any major errors.

Chapter 12 - Conclusion

12.1 Reference - Display System Conclusions

The reference - display system, under simulated operating room conditions, was found to be accurate to approximately 1 millimeter at the focal point and the equation of the focal plane was found to be qualitatively as accurate. The initial specification was to have the entire operational system error within 1 millimeter. The errors in other parts of the project, CT scanning, fiducials, etc., will certainly increase the resulting reference - display system error, however, the magnitude of this total error and the conceptual success and resulting project applicability cannot be determined until the system is actually used with a patient in the operating room.

Up to this point the project has been quite successful and hopefully the CT image reconstruction phase will completely prove the concept of integrating CT scanning and the operating microscope.

12.2 Future Design

As mentioned in Chapter 4, redesigning the microscope stand might be a better way to determine the relative focal plane - CT scan positions. Although it has not been determined as being cost effective, this design could take into account all the surgeon's needs and constraints while

providing a microprocessor-based system to determine, via position transducers the focal plane with respect to a fixed CT coordinate system. Since the present system is most sensitive to focusing error, the microscope optics could be redesigned to minimize the depth of field.

The display system could be improved by incorporating a high resolution color CRT with thinner beam splitter and reducing the extension of the CRT from the optical axis.

The optimal computer system design would directly receive the CT scan data from the scanning computer and process it right in the operating room. The reconstruction and display process could be done with the hardware of the present generation CT scanners, reducing the calculation time.

A design of this magnitude and expense could be a future goal.

12.3 Future Work

The future work on the current project will primarily involve the design of CT scan reconstruction software. Although contours will be developed initially, the algorithms should be adaptable to grey scale information. An anatomic brain atlas could also be developed to indicate important neurological structures.

An important feature that should be added to the reference - display system is feedback. If a 3-D trackball

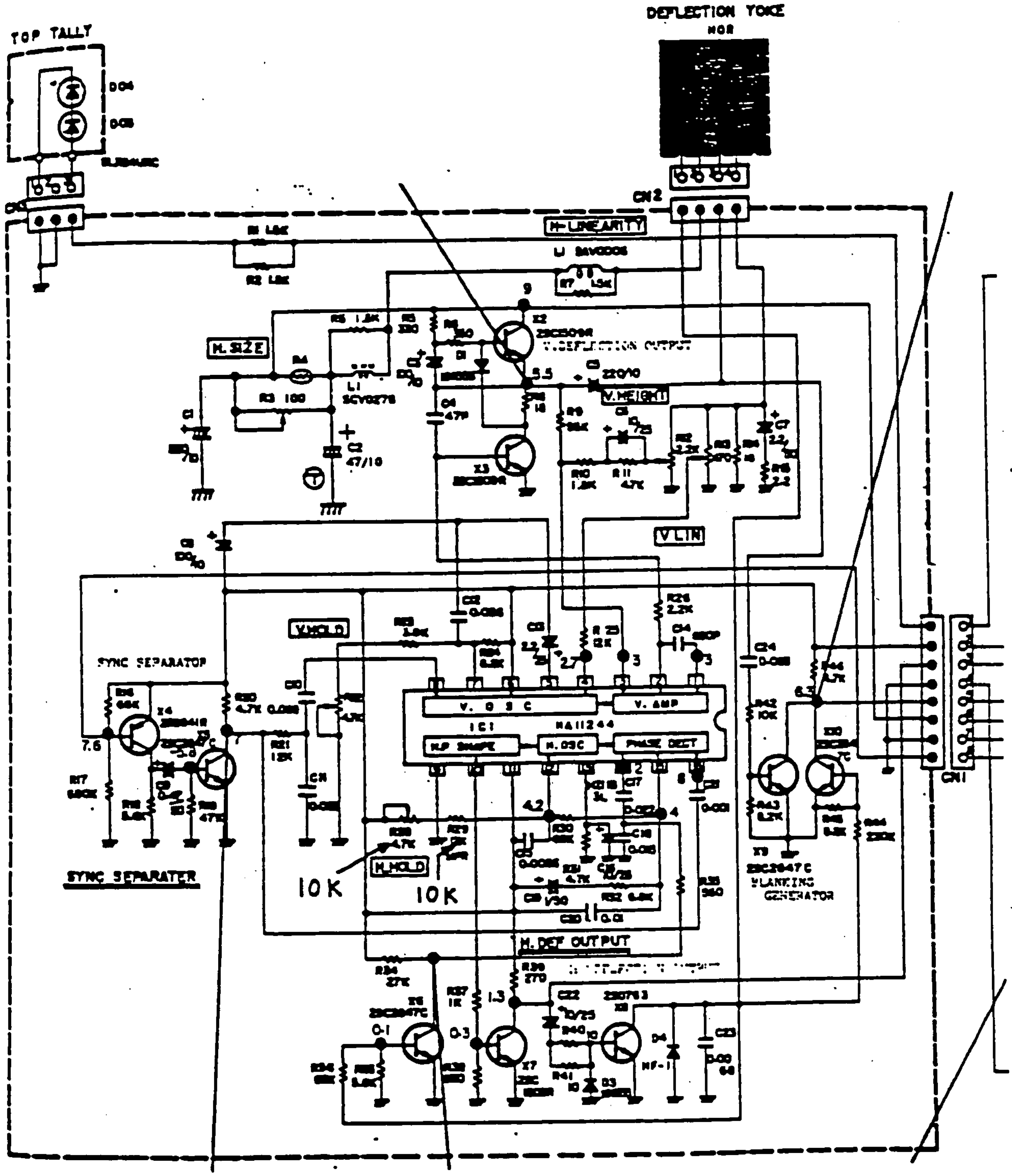
controlled the position of the CRT image, the surgeon could compensate for obvious reconstructed slice reference errors by correcting the image placement according to visible anatomic landmarks. The results of focusing error and other disturbances, which are significant and more or less fixed, could then be eliminated in successive slices by storing the offset values from the trackball.

APPENDICES

Appendix A - CRT Schematic Changes

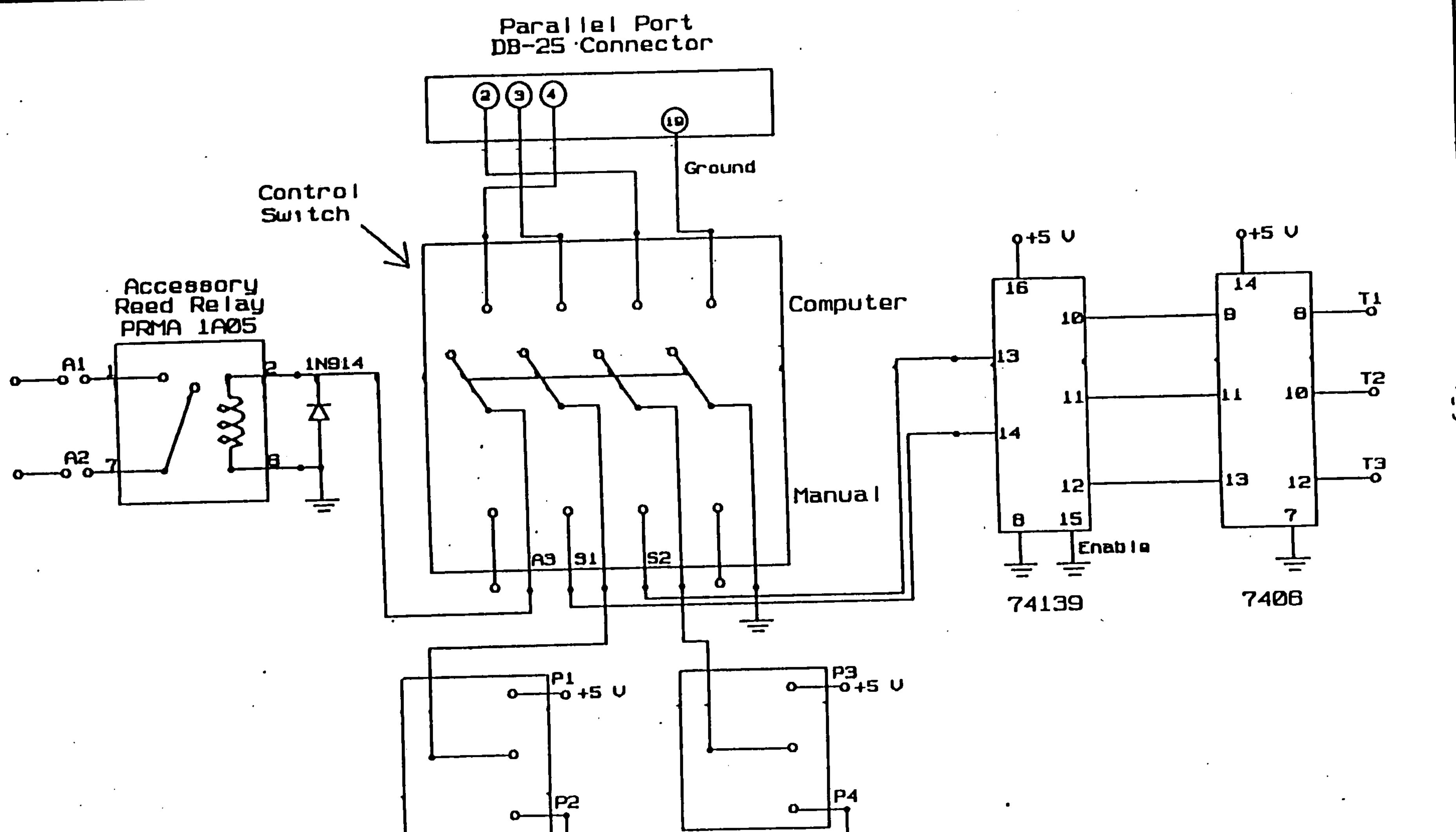
This appendix indicates the electronic changes to the J.V.C. model vf-1900 viewfinder (miniature CRT) used to display the reconstructed CT image.

The horizontal hold potentiometer, R28 was changed from 4.7 k to 10 k, and resistor R29 was changed from 12 k to 10 k. These changes will now allow more adjustment of the horizontal hold and provide a stable image for the Treatment Planning Computer display.


TOP TALLY
DEFLECTION YOKE
CN2
H-LINEARITY
H.SIZE
V.HEIGHT
V.LIN
V.HOLD
SYNC SEPARATOR
V. O S C
V. AMP
IC1
H.OSC
PHASE DET
H.HOLD
10K
10K
SYNC SEPARATER
H.DEF OUTPUT
BLANKING
GENERATOR
CN1

Appendix B - Multiplexer Schematic and Layout

This appendix contains the schematics and layouts of the spark gap multiplexer described in Chapter 8.



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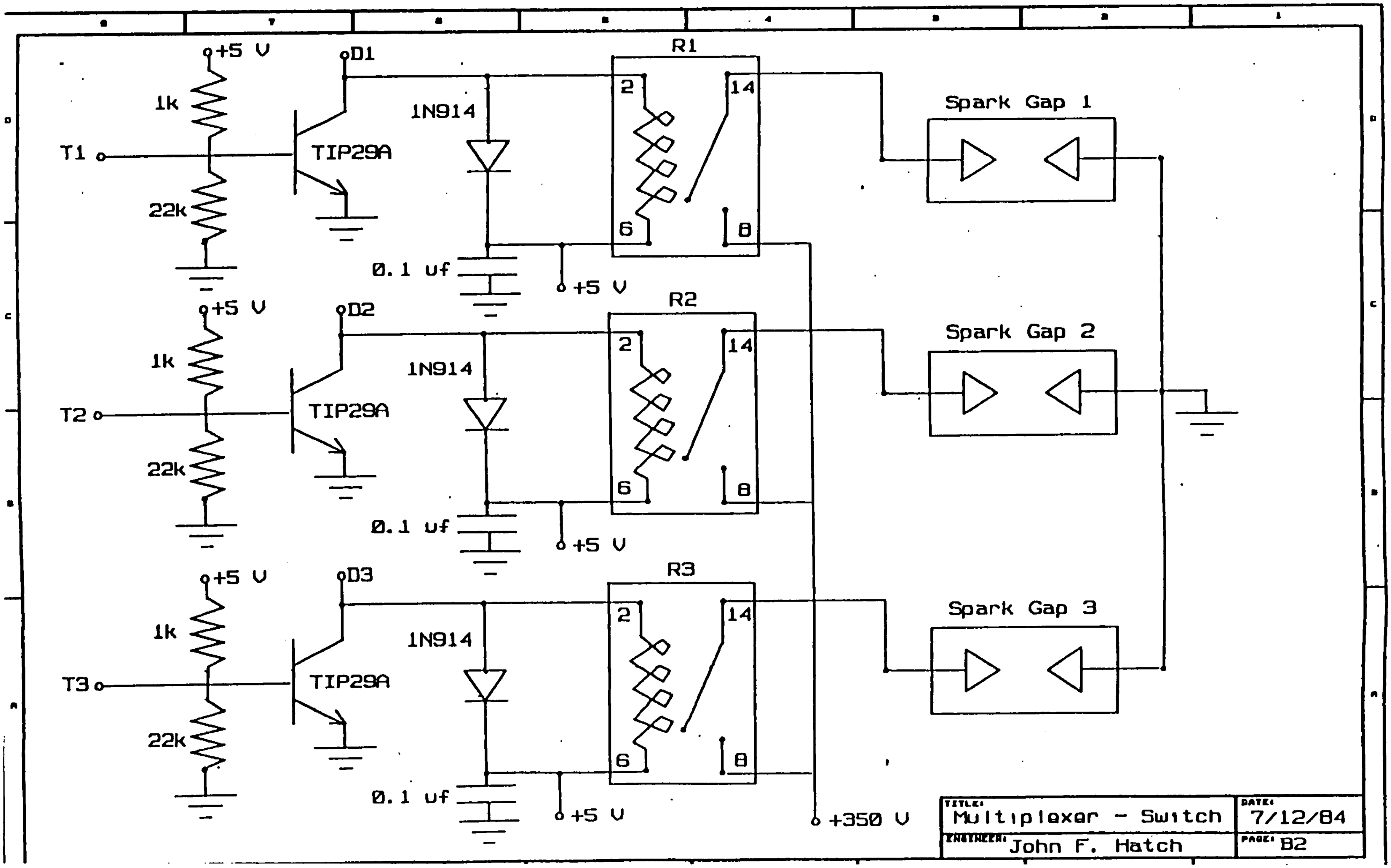
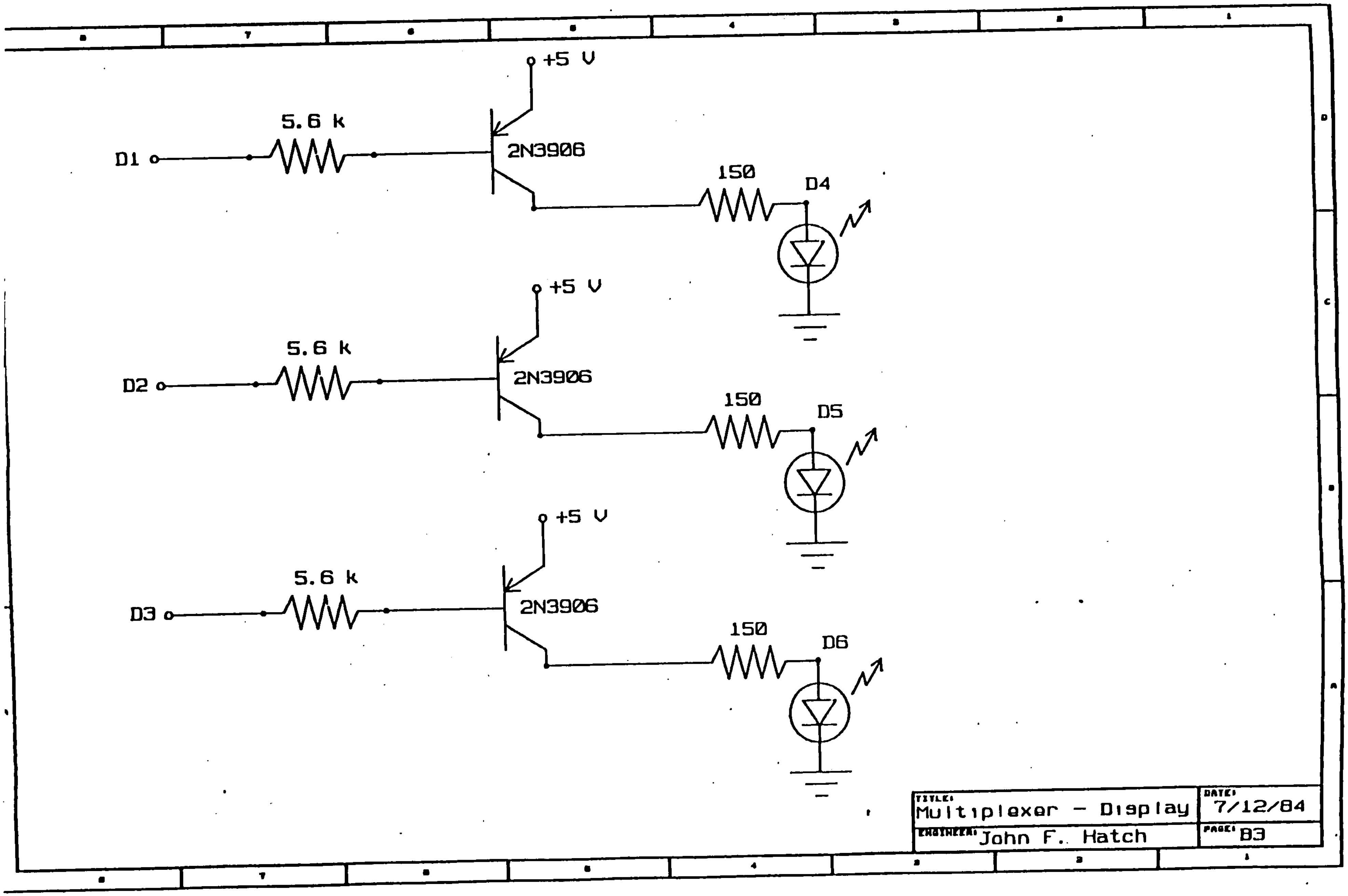
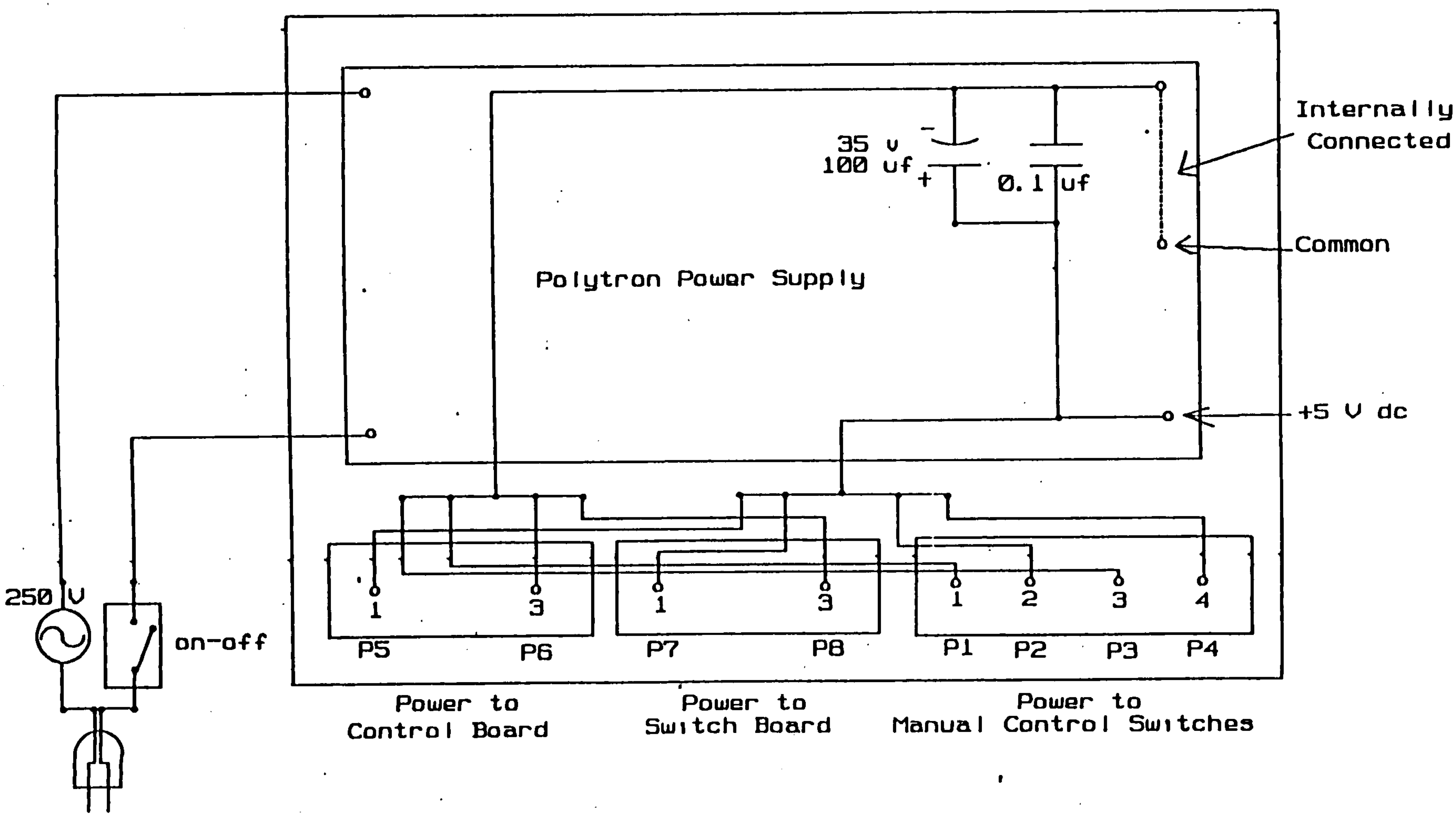
ENGINEER: John F. Hatch
DATE: 7/11/84
PAGE: B1



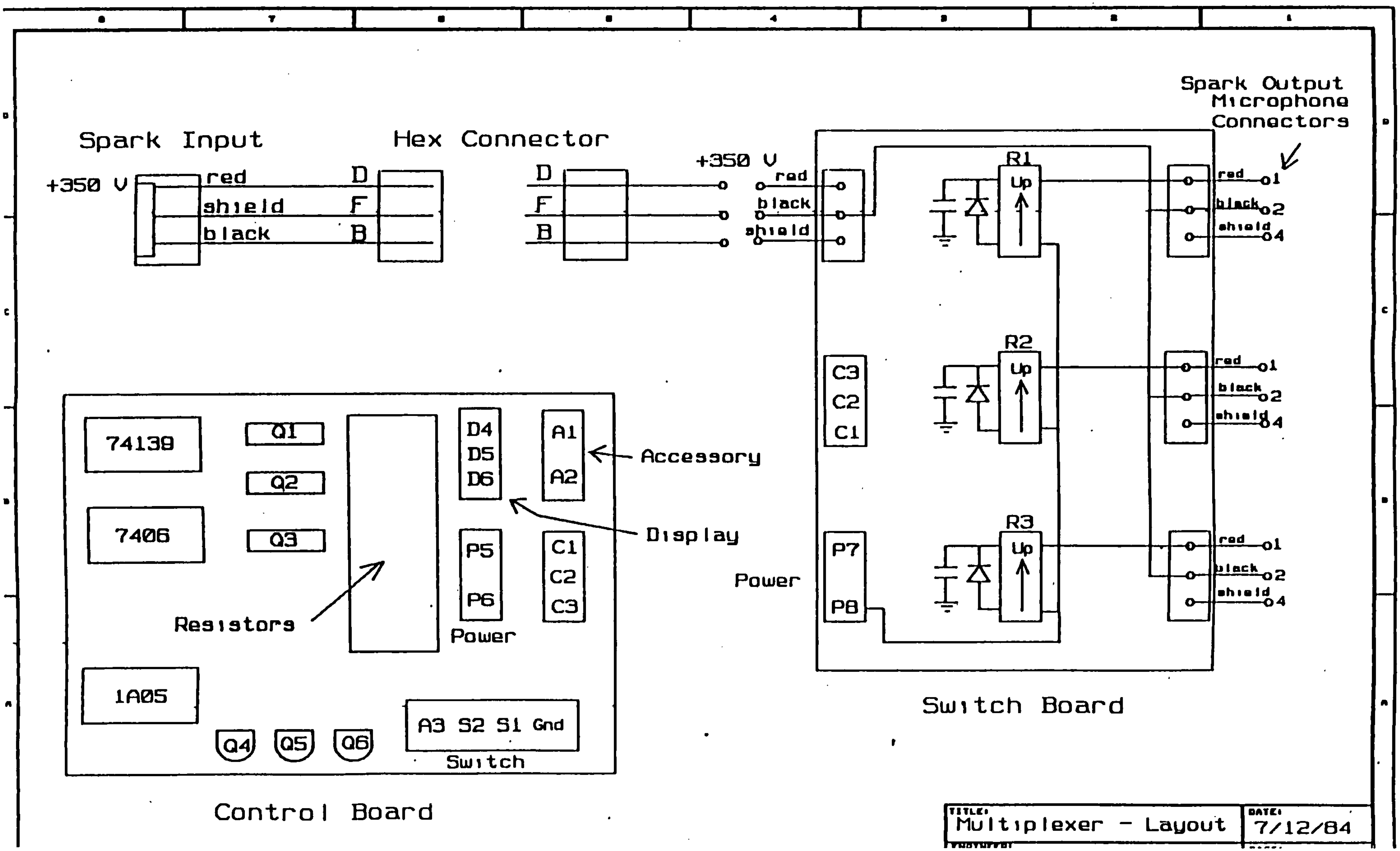
+5 V
D1
1k
T1
TIP29A
22k
1N914
0.1 uf
+5 V
R1
2
14
6
8
Spark Gap 1
+5 V
D2
1k
T2
TIP29A
22k
1N914
0.1 uf
+5 V
R2
2
14
6
8
Spark Gap 2
+5 V
D3
1k
T3
TIP29A
22k
1N914
0.1 uf
+5 V
R3
2
14
6
8
Spark Gap 3
+350 V
TITLE:
Multiplexer - Switch
DATE:
7/12/84
ENGINEER:
John F. Hatch
PAGE:
B2


+5 V
5.6 k
D1
2N3906
150
D4
+5 V
5.6 k
D2
2N3906
150
D5
+5 V
5.6 k
D3
2N3906
150
D6
TITLE:
Multiplexer - Display
DATE:
7/12/84
ENGINEER:
John F. Hatch
PAGE:
B3

Power Supply Board Schematic and Layout



TITLE: Multiplexer - Power	DATE: 7/12/84
ENGINEER: John F. Hatch	PAGE: B4


Spark Input
+350 V
red
shield
black
Hex Connector
D
F
B
+350 V
red
black
shield
Spark Output
Microphone
Connectors
R1
R2
R3
Up
1
2
4
C3
C2
C1
P7
P8
Power
Switch Board
74139
7406
1A05
Q1
Q2
Q3
Q4
Q5
Q6
D4
D5
D6
A1
A2
Accessory
Display
P5
P6
Power
C1
C2
C3
Resistors
A3 S2 S1 Gnd
Switch
Control Board
TITLE:
Multiplexer - Layout
DATE:
7/12/84

Appendix C - Software and Documentation

This appendix contains the software described in Chapter 9.

```
10 '
20 ' APPENDIX C
30 '
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50 ' SCANNING AND THE OPERATING MICROSCOPE
60 '
70 ' FILENAME: FPL
80 '
90 ' PROGRAMMER: JOHN F. HATCH
100 ' DATE: AUGUST, 1984
110 '
120 ' NOTE: REFER TO CHAPTER 6 IN THESIS FOR EQUATIONS,
130 ' AND REFERENCE 10 FOR ALGORITHMS.
140 '
150 ' THIS FILE DETERMINES THE COORDINATES OF THE FOCAL,
160 ' NORMAL AND ORIENTATION POINTS IN OBLIQUE SPARK GAP COORDINATES
170 ' FOR BOTH THE SITTING AND SUPINE SPARK GAP BRACKETS, AND STORES
180 ' THEM IN FILES SIT AND SUP.
190 '
200 OPTION BASE 1      ' SET LOWER ARRAY INDEX TO 1 FOR CONVENIENCE
210 '
220 ' ALLOCATE SPACE FOR ARRAYS
230 ' NOTE: ARRAY NAMES FOLLOWED BY A "#" SIGN ARE DOUBLE PRECISION
240 '
250 DIM J#(3,3)        ' JACOBIAN MATRIX COEFFICIENTS
260 DIM I#(3,3)        ' JACOBIAN MATRIX INVERSE
270 DIM SRMEAN(3,3)    ' MEAN SLANT RANGES
280 DIM SDATA(4,3,3)   ' SLANT RANGE DATA
290 DIM FOCAL(3,3)     ' OBLIQUE SPARK GAP COORDINATES OF THE FOCAL, NORMAL
300 '                    AND ORIENTATION POINTS
310 DIM NSOL(3,3)      ' COORDINATE SOLUTIONS TO NEWTON
320 DIM FX(3,3)        ' FIXED GRID COORDINATE SYSTEM
330 DIM MV#(3)         ' ITERATION VARIABLE (N-1)
340 DIM M#(100,3)      ' ITERATION VARIABLES
350 DIM SL(3)          ' SLANT RANGE DATA
360 DIM T(3)           ' ITERATION ERRORS
370 DIM DIST(3,3)      ' MICROPHONE-FOCAL POINT DISTANCES
380 DIM MIKE(3,3)      ' MICROPHONE COORDINATES IN FIXED GRID COORDINATE SYSTEM
390 DIM NPOINT(3)      ' NORMAL POINT COORDINATES IN FIXED GRID COORDINATE SYS.
400 DIM OPOINT(3)      ' ORIENTATION POINT COORDINATES IN FIXED GRID SYSTEM
410 DIM GRID(3,3)      ' COORDINATES OF MICROPHONE PLANE GRID
420 DIM SLANT(150,3)   ' SLANT RANGES
430 DIM F#(4)          ' ITERATIVE SOLUTION TO NEWTON
440 '
450 ' MEASURED DISTANCES BETWEEN SPARK GAPS IN CM.
460 S12=30.041         ' SPARK GAP 1 - SPARK GAP 2
470 S23=29.995         ' SPARK GAP 2 - SPARK GAP 3
480 S31=29.657         ' SPARK GAP 3 - SPARK GAP 1
490 '
500 CW=(S12^2+S31^2-S23^2)/(2*S12*S31)   ' COSINE OF ANGLE W, S2-S1-S3 EQN. 6.1
510 S2W=1-CW*CW                          ' SINE SQUARED OF ANGLE W, S2-S1-S3
520 '
530 ' IGNORE SLANT RANGE DATA FROM MICROPHONE MNOT
540  MNOT=4
550 '
560 PRINT
570 PRINT"WHICH SPARK GAP BRACKET WILL BE USED: SITTING (SIT) OR SUPINE (SUP)";
580 INPUT BRACK$
590 '
600 ' IF THE SITTING BRACKET IS USED SET FFLAG TO 1. IF THE SUPINE BRACKET
610 ' IS USED SET FFLAG TO 0.
620 '
630 IF BRACK$="SIT" THEN FFLAG=1: GOTO 650
640 IF BRACK$="SUP" THEN FFLAG=0 ELSE GOTO 560
650 '
```

```
660 PRINT
670 PRINT"TURN ON DIGITIZER AND SPARK GAP MULTIPLEXER."
680 PRINT
690 PRINT"NOTE:  THE DIGITIZER/COMPUTER COMMUNICATIONS MAY FAIL INITIALLY."
700 PRINT"DO NOT WORRY - THIS IS NORMAL.  JUST RETYPE 'FPL' WITHOUT TURNING"
710 PRINT"OFF THE DIGITIZER AND YOU SHOULD HAVE NO PROBLEM."
720 '
730 ' CALL SUBROUTINE FPLANE TO DETERMINE THE OBLIQUE SPARK GAP COORDINATES
740 ' OF THE FOCAL, NORMAL AND ORIENTATION POINTS
750 '
760 GOSUB 1170 ' CALL FPLANE
770 '
780 ' NOW THAT THE RELATIONSHIP BETWEEN THE SPARK GAPS AND THE FOCAL PLANE
790 ' HAS BEEN ESTABLISHED, STOP THE PROGRAM.
800 '
810 STOP
820 '
830 ' SUBROUTINE: DISTANCE
840 '
850 ' THIS SUBROUTINE CALCULATES THE DISTANCE FROM THE FOCAL POINT IN OBLIQUE
860 ' SPARK GAP COORDINATES AND THE MICROPHONES.
870 '
880 ' INPUTS: FOCAL(1,COORD) - OBLIQUE SPARK GAP COORDINATES OF FOCAL POINT:
890 '         SL(POINT) - SLANT RANGE DISTANCE TO MICROPHONES:
900 '         CW - COSINE OF ANGLE W, S2-S1-S3 (SPARK GAPS):
910 '         S2W - SINE SQUARED OF ANGLE W, S2-S1-S3 (SPARK GAPS)
920 ' OUTPUT: D - DISTANCE FROM FOCAL POINT TO MICROPHONE
930 '
940 ' POINT 1 - OBLIQUE MICROPHONE COORDINATES
950 '
960 ' CALCULATE PROJECTIONS OF SLANT 1 ON X AND Y SPARK AXES
970 XP1=(SL(1)^2+S31^2-SL(3)^2)/(2*S31)    ' EQN. 6.3
980 YP1=(SL(1)^2+S12^2-SL(2)^2)/(2*S12)    ' EQN. 6.4
990 '
1000 ' CALCULATE OBLIQUE COORDINATES OF POINT 1
1010 X1=(XP1-YP1*CW)/S2W                   ' EQN. 6.8
1020 Y1=(YP1-XP1*CW)/S2W                   ' EQN. 6.9
1030 Z1=(SL(1)^2-X1^2-Y1^2-2*X1*Y1*CW)^.5  ' EQN. 6.12
1040 '
1050 ' POINT 2 - FOCAL POINT COORDINATES
1060 '
1070 X2=FOCAL(1,1)
1080 Y2=FOCAL(1,2)
1090 Z2=FOCAL(1,3)
1100 '
1110 ' CALCULATE DISTANCE D USING OBLIQUE DISTANCE FORMULA, EQN. 6.14
1120 '
1130 D=(X2-X1)^2+(Y2-Y1)^2+(Z2-Z1)^2+2*(X2-X1)*(Y2-Y1)*CW
1140 '
1150 RETURN
1160 '
1170 ' SUBROUTINE: FPLANE
1180 '
1190 ' THIS SUBROUTINE DETERMINES THE OBLIQUE SPARK GAP COORDINATES OF THE
1200 ' FOCAL, NORMAL AND ORIENTATION POINTS FOR THE SITTING OR SUPINE SPARK
1210 ' BRACKET.
1220 '
1230 ' OUTPUT: FOCAL(POINT,COORD) - OBLIQUE SPARK GAP COORDINATES OF THE FOCAL,
1240 '         NORMAL AND ORIENTATION POINTS
1250 ' SUBROUTINES NEEDED: SRINP, NEWTON, STORE, DISTANCE
1260 '
1270 PRINT
1280 PRINT"ANCHOR THE FOURTH SPARK GAP UNDER THE MICROPHONES SUCH THAT IT CAN"
1290 PRINT"BE EASILY FOCUSED UPON.  CONNECT THE SPARK GAP TO THE 'SPARK GAP 1'"
1300 PRINT"OUTPUT ON THE SPARK GAP MULTIPLEXER. MAKE SURE MICROSCOPE IS OUT OF"
1310 PRINT"THE WAY.  DO NOT MOVE OR DISTURB THIS SPARK GAP WITH RESPECT TO THE"
```

```
1320 PRINT"MICROPHONES ONCE IT HAS BEEN ACTIVATED (FIRED) BY THE DIGITIZER!"
1330 '
1340 ' SET SPARK GAP FLAG TO 1 INDICATING ONLY ONE SPARK GAP MUST BE FIRED
1350 SFLAG=1
1360 '
1370 ' FIRE FOURTH SPARK GAP TO DETERMINE THE DISTANCES BETWEEN THE FOCAL POIN
1380 ' AND THE MICROPHONES.
1390 '
1400 GOSUB 4070 ' CALL SRINP
1410 '
1420 ' STORE THE SQUARED SLANT RANGES IN ARRAY DIST TO BE USED BY NEWTON
1430 FOR MK=1 TO 3                       ' STEP THROUGH EACH MICROPHONE
1440  DIST(MK,1)=(SRMEAN(MK,1))^2 ' MICROPHONE - FOCAL POINT DISTANCES
1450 NEXT MK                             ' NEXT MICROPHONE
1460 '
1470 PRINT
1480 PRINT"CONNECT ALL THREE SPARK GAPS TO THE SPARK GAP MULTIPLEXER AND THEN"
1490 PRINT"FOCUS THE MICROSCOPE, AT THE HIGHEST MAGNIFICATION (2.5), ON THE"
1500 PRINT"TIP OF THE FOURTH SPARK GAP, MAKING SURE THE FOURTH SPARK GAP IS"
1510 PRINT"NOT DISTURBED."
1520 '
1530 ' COLLECT SLANT RANGES FOR FOCUSED MICROSCOPE
1540 GOSUB 4070    ' CALL SRINP
1550 '
1560 ' CALCULATE THE OBLIQUE SPARK GAP COORDINATES OF THE THREE MICROPHONES
1570 ' GIVEN THEIR SLANT RANGES.
1580 '
1590 FOR MK=1 TO 3     ' STEP THROUGH EACH MICROPHONE
1600 '
1610 ' CALCULATE PROJECTIONS OF SLANT RANGE 1 ON THE X AND Y SPARK GAP AXES
1620 '
1630  XP=(SRMEAN(MK,1)^2+S31^2-SRMEAN(MK,3)^2)/(2*S31) ' EQN. 6.3
1640  YP=(SRMEAN(MK,1)^2+S12^2-SRMEAN(MK,2)^2)/(2*S12) ' EQN. 6.4
1650 '
1660 ' CALCULATE THE OBLIQUE COORDINATES OF MICROPHONE MK
1670  FX(MK,1)=(XP-YP*CW)/S2W     ' EQN. 6.8
1680  FX(MK,2)=(YP-XP*CW)/S2W     ' EQN. 6.9
1690  FX(MK,3)=(SRMEAN(MK,1)^2-FX(MK,1)^2-FX(MK,2)^2-2*FX(MK,1)*FX(MK,2)*CW)^.
1700 ' EQN. 6.12
1710 '
1720 NEXT MK              ' NEXT MICROPHONE
1730 '
1740 ' CALCULATE COORDINATES OF FOCAL POINT IN SPARK GAP COORDINATES BY SOLVIN
1750 ' THREE NONLINEAR DISTANCE EQUATIONS FOR THE THREE COORDINATES.
1760 '
1770 ' CALL SUBROUTINE NEWTON WITH NFLAG=1 WHICH WILL TAKE THE OBLIQUE
1780 ' MICROPHONE COORDINATES STORED IN ARRAY FX, AND THE DISTANCES STORED IN
1790 ' ARRAY DIST AND SOLVE EQN. 6.13.
1800 '
1810 NFLAG=1  ' SET FLAG TO 1 SUCH THAT NEWTON SOLVES EQUATIONS 6.13.
1820 GOSUB 5530 ' CALL NEWTON
1830 '
1840 ' STORE THE OBLIQUE COORDINATES OF THE FOCAL POINT, FROM SUBROUTINE NEWT(
1850 ' IN ARRAY FOCAL.
1860 '
1870 FOR COORD=1 TO 3                    ' STEP THROUGH X,Y,Z
1880  FOCAL(1,COORD)=NSOL(1,COORD)       ' STORE COORDINATE
1890 NEXT COORD                          ' NEXT COORDINATE
1900 '
1910 ' COLLECT THE SLANT RANGE DATA FOR THE GRID COORDINATE SYSTEM (FIG 9.1).
1920 ' THIS DATA IS THE DISTANCES FROM EACH OF THE THREE SPARK GAPS TO
1930 ' THE THREE MICROPHONES FOR GRID POINTS 1, 2 AND 3 (NORMAL TO THE
1940 ' Z AXIS OF THE GRID COORDINATE SYSTEM), AND THE NORMAL POINT ALONG
1950 ' THE OPTICAL AXIS.
1960 '
1970 PRINT"LOCATE THE GRID COORDINATE SYSTEM WITH THE PROTRACTOR, RESET THE"
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1980 PRINT"PROTRACTOR TO 0 DEGREES AND ANCHOR IT UNDER THE MICROSCOPE."
1990 PRINT
2000 '
2010 ' STORE FIXED CARTESIAN GRID COORDINATES
2020 GRID(1,1)=0: GRID(1,2)=10.246: GRID(1,3)=0
2030 GRID(2,1)=10.114: GRID(2,2)=0: GRID(2,3)=0
2040 GRID(3,1)=0: GRID(3,2)=0: GRID(3,3)=0
2050 '
2060 FOR PT=1 TO 4                    ' STEP THROUGH EACH POINT
2070  IF PT=1 THEN PRINT"FOCUS ON PT. 1"
2080  IF PT=2 THEN PRINT"FOCUS ON PT. 2"
2090  IF PT=3 THEN PRINT"FOCUS ON PT. 3 NORMAL TO GRID WITH THE CROSSHAIRS"
2100  IF PT=3 THEN PRINT"IN THE MICROSCOPE ALIGNED WITH THOSE OF THE"
2110  IF PT=3 THEN PRINT"PROTRACTOR SET AT 0 DEGREES. MAKE SURE THAT THE"
2120  IF PT=3 THEN PRINT"FOCUSING KNOB IS TURNED SUCH THAT THE MICROSCOPE IS"
2130  IF PT=3 THEN PRINT"AS CLOSE TO THE GRID COORDINATE SYSTEM AS POSSIBLE."
2140  IF PT=4 THEN PRINT"MOVE MICROSCOPE ALONG OPTICAL AXIS, AWAY FROM GRID"
2150  IF PT=4 THEN PRINT"BY TURNING THE MICROSCOPE FOCUSING KNOB."
2160 '
2170 ' COLLECT SLANT RANGE DATA
2180 GOSUB 4070      ' CALL SRINP
2190 '
2200  FOR MK=1 TO 3                         ' STEP THROUGH EACH MICROPHONE
2210   FOR SPK=1 TO 3                       ' STEP THROUGH EACH SPARK GAP
2220 ' STORE SLANT RANGE DATA IN ARRAY SDATA
2230    SDATA(PT,MK,SPK)=SRMEAN(MK,SPK)
2240   NEXT SPK                             ' NEXT SPARK GAP
2250  NEXT MK                               ' NEXT MICROPHONE
2260 NEXT PT                                ' NEXT GRID POINT
2270 '
2280 ' CALCULATE DISTANCES FROM GRID POINTS 1, 2 AND 3 TO MICROPHONES
2290 '
2300 FOR PT=1 TO 3             ' STEP THROUGH EACH GRID POINT
2310  FOR MK=1 TO 3            ' STEP THROUGH EACH MICROPHONE
2320   FOR SPK=1 TO 3          ' STEP THROUGH EACH SPARK GAP
2330 ' STORE SLANT RANGES IN VECTOR SL
2340    SL(SPK)=SDATA(PT,MK,SPK)
2350   NEXT SPK                ' NEXT SPARK GAP
2360 '
2370 ' CALCULATE THE DISTANCES FROM THE FOCAL POINT (POINTS 1, 2 AND 3)
2380 ' TO THE MICROPHONES BY CALLING SUBROUTINE DISTANCE GIVEN SLANT RANGES
2390 ' STORED IN VECTOR SL.
2400 '
2410   GOSUB 830               ' CALL DISTANCE
2420 '
2430 ' STORE SQUARED DISTANCES BETWEEN FOCAL POINT AND MICROPHONES IN ARRAY
2440 ' DIST FOR SUBROUTINE NEWTON.
2450 '
2460   DIST(PT,MK)=D
2470  NEXT MK                  ' NEXT MICROPHONE
2480 NEXT PT                   ' NEXT GRID POINT
2490 '
2500 ' STORE GRID COORDINATES IN FIXED ARRAY FOR SUBROUTINE NEWTON
2510 FOR PT=1 TO 3                      ' STEP THROUGH EACH GRID POINT
2520  FOR COORD=1 TO 3                  ' STEP THROUGH X,Y,Z
2530   FX(PT,COORD)=GRID(PT,COORD)      ' STORE GRID COORDINATES IN ARRAY FX
2540  NEXT COORD                        ' NEXT COORDINATE
2550 NEXT PT                            ' NEXT GRID POINT
2560 '
2570 ' CALCULATE MICROPHONE COORDINATES
2580 '
2590 PRINT"CALCULATING MICROPHONE COORDINATES..."
2600 '
2610 NFLAG=0    ' SET NFLAG TO 0 SUCH THAT NEWTON WILL SOLVE EQUATIONS 6.15.
2620 GOSUB 5530     ' CALL NEWTON TO SOLVE FOR THE GRID MICROPHONE COORDINATE
2630 '
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2640 ' STORE MICROPHONE COORDINATES
2650 '
2660 FOR MK=1 TO 3                        ' STEP THROUGH EACH MICROPHONE
2670  FOR COORD=1 TO 3                    ' STEP THROUGH X,Y,Z
2680   MIKE(MK,COORD)=NSOL(MK,COORD)      ' STORE NEWTON SOLUTIONS IN ARAAY MIKE
2690  NEXT COORD                          ' NEXT COORDINATE
2700 NEXT MK                              ' NEXT MICROPHONE
2710 '
2720 ' CALCULATE THE DISTANCES FROM THE NORMAL POINT (DETERMINED WHEN THE
2730 ' MICROSCOPE WAS MOVED ALONG THE OPTICAL AXIS AWAY FROM THE X-Y PLANE
2740 ' OF THE GRID COORDINATE SYSTEM) TO EACH OF THE THREE MICROPHONES BY
2750 ' CALLING SUBROUTINE DISTANCE.
2760 '
2770 FOR MK=1 TO 3                        ' STEP THROUGH EACH MICROPHONE
2780  FOR SPK=1 TO 3                      ' STEP THROUGH EACH SPARK GAP
2790   SL(SPK)=SDATA(4,MK,SPK)            ' STORE SLANT RANGE DATA IN VECTOR SL
2800  NEXT SPK                            ' NEXT SPARK GAP
2810 '
2820 ' CALL SUBROUTINE DISTANCE TO DETERMINE THE DISTANCES BETWEEN THE
2830 ' NORMAL POINT AND THE MICROPHONES.
2840 '
2850  GOSUB 830   ' CALL DISTANCE
2860 '
2870 ' STORE THE SQUARE OF THE DISTANCE IN ARRAY DIST
2880 '
2890  DIST(MK,1)=D
2900 '
2910 NEXT MK                              ' NEXT MICROPHONE
2920 '
2930 ' STORE MICROPHONE COORDINATES IN ARRAY FX FOR SUBROUTINE NEWTON
2940 '
2950 FOR MK=1 TO 3                        ' STEP THROUGH EACH MICROPHONE
2960  FOR COORD=1 TO 3                    ' STEP THROUGH X,Y,Z
2970   FX(MK,COORD)=MIKE(MK,COORD)        ' STORE COORDINATES
2980  NEXT COORD                          ' NEXT COORDINATE
2990 NEXT MK                              ' NEXT MICROPHONE
3000 '
3010 ' CALCULATE THE NORMAL POINT COORDINATES IN THE FIXED GRID COORD. SYSTEM
3020 '
3030 PRINT"CALCULATING NORMAL POINT COORDINATES..."
3040 '
3050 NFLAG=2    ' SET NFLAG TO 2 SUCH THAT NEWTON WILL SOLVE EQUATIONS 6.16
3060 GOSUB 5530    ' CALL NEWTON
3070 '
3080 ' STORE NORMAL POINT GRID COORDINATES IN VECTOR NPOINT
3090 '
3100 FOR COORD=1 TO 3                     ' STEP THROUGH X,Y,Z
3110  NPOINT(COORD)=NSOL(1,COORD)         ' STORE GRID COORDINATES
3120 NEXT COORD                           ' NEXT COORDINATE
3130 '
3140 ' THE NEXT STEP IS TO CALCULATE THE COORDINATES OF THE MICROPHONES IN THE
3150 ' OBLIQUE SPARK GAP COORDINATE SYSTEM (WITH THE MICROSCOPE AT THE NORMAL
3160 ' POINT.) WITH THESE COORDINATES IN ARRAY FX, AND THE DISTANCES FROM EACH
3170 ' MICROPHONE TO THE NORMAL POINT KNOWN BY APPLYING EQUATION 6.15 TO THE
3180 ' COORDINATES IN ARRAY MIKE AND VECTOR NPOINT, SUBROUTINE NEWTON WILL
3190 ' SOLVE THE THREE NONLINEAR EQUATIONS OF EQUATION 6.17 FOR THE OBLIQUE
3200 ' SPARK GAP COORDINATES OF THE NORMAL POINT.
3210 '
3220 FOR MK=1 TO 3        ' STEP THROUGH EACH MICROPHONE
3230 '
3240 ' CALCULATE PROJECTION OF SLANT RANGE 1 ONTO THE X AND Y SPARK AXES.
3250 '
3260 XP=(SDATA(3,MK,1)^2+S31^2-SDATA(3,MK,3)^2)/(2*S31)  ' EQN. 6.3
3270 YP=(SDATA(3,MK,1)^2+S12^2-SDATA(3,MK,2)^2)/(2*S12)  ' EQN. 6.4
3280 '
3290 ' CALCULATE THE OBLIQUE SPARK GAP COORDINATES OF EACH MICROPHONE AND
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3300 ' STORE IN ARRAY FX FOR SUBROUTINE NEWTON.
3310 '.
3320 FX(MK,1)=(XP-YP*CW)/S2W    ' EQN. 6.9
3330 FX(MK,2)=(YP-XP*CW)/S2W    ' EQN. 6.9
3340 FX(MK,3)=(SDATA(3,MK,1)^2-FX(MK,1)^2-FX(MK,2)^2-2*FX(MK,1)*FX(MK,2)*CW)^.5
3350 ' EQN. 6.12
3360 '
3370 ' CALCULATE THE DISTANCE BETWEEN THE NORMAL POINT AND EACH MICROPHONE IN
3380 ' THE GRID COORDINATE SYSTEM.
3390 '
3400 DIST(MK,1)=(MIKE(MK,1)-NPOINT(1))^2+(MIKE(MK,2)-NPOINT(2))^2+(MIKE(MK,3)-NP
OINT(3))^2
3410 '
3420 NEXT MK              ' NEXT MICROPHONE
3430 '
3440 ' SOLVE FOR THE OBLIQUE COORDINATES OF THE NORMAL POINT BY CALLING
3450 ' SUBROUTINE NEWTON.
3460 '
3470 NFLAG=1 ' SET NFLAG TO 1 SUCH THAT NEWTON SOLVES EQUATIONS 6.17.
3480 GOSUB 5530 ' CALL NEWTON
3490 '
3500 ' STORE OBLIQUE NORMAL POINT COORDINATES IN ARRAY FOCAL.
3510 '
3520 FOR COORD=1 TO 3                     'STEP THROUGH X,Y,Z
3530  FOCAL(2,COORD)=NSOL(1,COORD)        ' STORE COORDINATE
3540 NEXT COORD                           ' NEXT COORDINATE
3550 '
3560 PRINT"CALCULATING ORIENTATION POINT COORDINATES..."
3570 '
3580 ' CALCULATE THE COORDINATES OF THE PROJECTED GRID POINT 1 ONTO THE FOCAL
3590 ' PLANE - WHICH IS THE ORIENTATION POINT, STORED IN VECTOR OPOINT.
3600 '
3610 KK=NPOINT(1)^2+NPOINT(2)^2+NPOINT(3)^2
3620 T=(-NPOINT(1)*GRID(1,1)-NPOINT(2)*GRID(1,2)-NPOINT(3)*GRID(1,3))/KK
3630 ' EQN. 6.26
3640 '                                               ' STEP THROUGH X,Y,Z
3650 FOR COORD=1 TO 3
3660  OPOINT(COORD)=NPOINT(COORD)*T+GRID(1,COORD)
3670 NEXT COORD                                      ' NEXT COORDINATE
3680 '
3690 ' AS WITH THE NORMAL POINT, THE OBLIQUE SPARK GAP COORDINATES OF THE
3700 ' ORIENTATION POINT MUST BE KNOWN.  FIRST THE OBLIQUE COORDINATES OF THE
3710 ' MICROPHONES MUST BE DETERMINED WITH THE MICROSCOPE FOCUSED ON THE GRID
3720 ' ORIGIN.  THEN THE DISTANCES BETWEEN THE MICROPHONES AND THE ORIENTATION
3730 ' POINT MUST BE CALCULATED, AND THIS INFORMATION USED WITH THE SUBROUTINE
3740 ' NEWTON TO CALCULATE THE OBLIQUE SPARK GAP COORDINATES OF THE ORIENTATION
3750 ' POINT.
3760 '
3770 FOR MK=1 TO 3           ' STEP THROUGH EACH MICROPHONE
3780 '
3790 ' CALCULATE THE DISTANCE BETWEEN THE ORIENTATION POINT AND THE MICROPHONES
3800 DIST(MK,1)=(MIKE(MK,1)-OPOINT(1))^2+(MIKE(MK,2)-OPOINT(2))^2+(MIKE(MK,3)-OP
OINT(3))^2
3810 NEXT MK                 ' NEXT MICROPHONE
3820 '
3830 ' SUBROUTINE NEWTON WILL THEN SOLVE EQUATIONS 6.27 FOR THE OBLIQUE
3840 ' SPARK GAP COORDINATES OF THE ORIENTATION POINT.
3850 '
3860 NFLAG=1 ' SET NFLAG TO 1 SUCH THAT NEWTON WILL SOLVE EQUATIONS 6.27.
3870 GOSUB 5530  ' CALL NEWTON
3880 '
3890 ' STORE OBLIQUE ORIENTATION POINT COORDINATES IN ARRAY FOCAL
3900 '
3910 FOR COORD=1 TO 3                 ' STEP THROUGH X,Y,Z
3920  FOCAL(3,COORD)=NSOL(1,COORD)    ' STORE COORDINATE
3930 NEXT COORD                       ' NEXT COORDINATE
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3940 '
3950 PRINT
3960 PRINT"THE OBLIQUE COORDINATES OF THE FOCAL, NORMAL AND ORIENTATION"
3970 PRINT"POINTS HAVE BEEN DETERMINED AND STORED IN ARRAY - ";BRACK$
3980 PRINT
3990 PRINT"READY TO RUN FILE: REG"
4000 ' STORE FOCAL POINT DATA IN FILE SIT IF FFLAG=1 OR SUP IF FFLAG=0
4010 '
4020 IF FFLAG=1 THEN GOSUB 7250 ' STORE SIT
4030 IF FFLAG=0 THEN GOSUB 7410 ' STORE SUP
4040 '
4050 RETURN
4060 '
4070 ' SUBROUTINE: SRINP
4080 '
4090 ' THIS FILE OPENS THE RS-232 PORT FOR DIGITIZER COMMUNICATIONS.
4100 ' CONTROLS THE SPARK GAP MULTIPLEXER. STORES THE SLANT RANGES
4110 ' IN AN ARRAY, AND DETERMINES THE STANDARD DEVIATIONS AND MEANS.
4120 '
4130 ' INPUT: MNOT - IGNORED MICROPHONE
4140 ' OUTPUT: SRMEAN(MIKE,SKGAP) - AVERAGE SLANT RANGES FOR EACH SPARK GAP
4150 '
4160 PRINT
4170 PRINT "*****PRESS ANY KEY WHEN FOCUSED/READY*****"
4180 PRINT
4190 '
4200 ' PAUSE UNTIL ANY KEY IS DEPRESSED
4210 P$=INKEY$: IF P$="" THEN 4210
4220 '
4230 IF SFLAG=1 THEN SMAX=0 ELSE SMAX=2 ' SET NUMBER OF SPARK GAPS
4240 '
4250 FOR SGAP=0 TO SMAX  ' SET MULTIPLEXER THROUGH PARALLEL PORT
4260 ' CHANGE SGAP TO SGAP1 FOR PROPER MULTIPLEXER SEQUENCING
4270  IF SGAP=0 THEN SGAP1=0
4280  IF SGAP=1 THEN SGAP1=2
4290  IF SGAP=2 THEN SGAP1=1
4300 '
4310 ' WRITE THE BINARY CODE FOR SGAP1 TO THE PARALLEL PORT ADDRESS 3BC HEX
4320  OUT &H3BC,SGAP1
4330 '
4340 ' OPEN RS-232 PORT. SET BAUD RATE AND PARITY
4350  OPEN "COM1:9600.O,7,1" AS #1
4360 '
4370   FLAG=1       ' INITIALIZE CHARACTER FLAG
4380   WHILE FLAG   ' SEARCH CHARACTER INPUT FOR ASCII LINE FEED IF FLAG=1
4390    S$=INPUT$(1,#1)
4400     IF ASC(S$)=10 THEN FLAG=0 ELSE FLAG=1
4410   WEND
4420 '
4430  W$=INPUT$(26,#1)    ' IGNORE FIRST VALUES (FROM LAST SLANT RANGES)
4440 '
4450  FOR I=1 TO 100      ' FIRE EACH SPARK GAP 100 TIMES.
4460 '
4470 ' MONITOR COMM. BUFFER, IF >40 CHARACTERS IN BUFFER TURN OFF DIGITIZER
4480 ' BY WRITING BINARY CODE 10 TO ADDRESS 3FC HEX - THE RS-232 PORT
4490 '
4500   IF LOC(1)>40 THEN OUT &H3FC,10 ELSE OUT &H3FC,11
4510 '
4520 ' INPUT SLANT RANGES AND INSERT DECIMAL POINTS TO READ DISTANCES IN CM.
4530 '
4540   A$=INPUT$(26,#1)    ' INPUT 26 CHARACTER STRING (4 SLANT RANGES)
4550 '
4560   C$=MID$(A$,1,6): CL$=LEFT$(C$,3): CR$=RIGHT$(C$,3): CC$=CL$+"."+CR$
4570   D$=MID$(A$,7,6): DL$=LEFT$(D$,3): DR$=RIGHT$(D$,3): DD$=DL$+"."+DR$
4580   E$=MID$(A$,13,6): EL$=LEFT$(E$,3): ER$=RIGHT$(E$,3): EE$=EL$+"."+ER$
4590   F$=MID$(A$,19,6): FL$=LEFT$(F$,3): FR$=RIGHT$(F$,3): FF$=FL$+"."+FR$
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4600 '
4610 ' STORE THE VALUE OF EACH CHARACTER STRING FOR EACH SLANT RANGE IN G1-4
4620   G1=VAL(CC$): G2=VAL(DD$): G3=VAL(EE$): G4=VAL(FF$)
4630 '
4640 ' IGNORE SLANT RANGE DATA FROM MICROPHONE MNOT AND STORE REMAINING
4650 ' SLANT RANGES IN P1-3
4660 '
4670   IF MNOT=1 THEN P1=G2: P2=G4: P3=G3
4680   IF MNOT=2 THEN P1=G1: P2=G3: P3=G4
4690   IF MNOT=3 THEN P1=G4: P2=G2: P3=G1
4700   IF MNOT=4 THEN P1=G3: P2=G1: P3=G2
4710 '
4720 ' STORE SLANT RANGES IN ARRAY SLANT
4730   SLANT(I,1)=P1: SLANT(I,2)=P2: SLANT(I,3)=P3
4740 '
4750  NEXT I     ' GET NEXT SET OF FOUR SLANT RANGES
4760 '
4770 CLOSE #1    ' SUPPRESS DIGITIZER COMMUNICATION
4780 '
4790 ' CALCULATE MEAN SLANT RANGE VALUES
4800 '
4810 C1=0: C2=0: C3=0                ' INITIALIZE SLANT RANGE SUM
4820 BAD1=0: BAD2=0: BAD3=0          ' INITIALIZE BAD DATA COUNTER
4830 CNT1=0: CNT2=0: CNT3=0          ' INITIALIZE NUMBER OF SLANT RANGES
4840 '
4850 FOR I=1 TO 100                  ' STEP THROUGH EACH SLANT RANGE
4860 '
4870 ' TEST EACH SLANT RANGE. IF LESS THAN MAX VALUE OF 245 CM. ADD TO SUM.
4880 ' IF A VALUE IS GREATER THAN 245 CM., INCREMENT BAD COUNTER AND IGNORE
4890 ' THE BAD DATA.  IF 5 BAD VALUES ARE DETECTED, THE MICROPHONE IN ERROR
4900 ' MIGHT BE BLOCKED, AN ERROR MESSAGE IS DISPLAYED AND SRINP IS RECALLED.
4910 '
4920  IF SLANT(I,1)<245 THEN C1=C1+SLANT(I,1): CNT1=CNT1+1: ELSE BAD1=BAD1+1
4930 '
4940  IF BAD1>=5 THEN PRINT "BAD DATA FROM X MIKE-TRY AGAIN.": GOTO 4170
4950 '
4960  IF SLANT(I,2)<245 THEN C2=C2+SLANT(I,2): CNT2=CNT2+1: ELSE BAD2=BAD2+1
4970 '
4980  IF BAD2>=5 THEN PRINT "BAD DATA FROM ZERO MIKE-TRY AGAIN.": GOTO 4170
4990 '
5000  IF SLANT(I,3)<245 THEN C3=C3+SLANT(I,3): CNT3=CNT3+1: ELSE BAD3=BAD3+1
5010 '
5020  IF BAD3>=5 THEN PRINT "BAD DATA FROM Y MIKE-TRY AGAIN.": GOTO 4170
5030 '
5040 NEXT I     ' TEST NEXT SET OF SLANT RNAGES
5050 '
5060 ' CALCULATE THE AVERAGE SLANT RANGE VALUES
5070 SMEAN1=C1/CNT1: SMEAN2=C2/CNT2: SMEAN3=C3/CNT3
5080 '
5090 ' CALCULATE STANDARD DEVIATIONS OF SLANT RANGE VALUES TO DETERMINE IF
5100 ' THERE IS UNACCEPTABLE VARIATION IN THE DATA, IE. A AIR DISTURBANCE.
5110 '
5120 C1=0: C2=0: C3=0                ' INITIALIZE SLANT RANGE SUM
5130 CNT1=0: CNT2=0: CNT3=0          ' INITIALIZE NUMBER OF SLANT RANGES
5140 '
5150 FOR I=1 TO 100                  ' STEP THROUGH EACH SLANT RANGE
5160 '
5170  IF SLANT(I,1)<245 THEN C1=C1+(SLANT(I,1)-SMEAN1)^2: CNT1=CNT1+1
5180  IF SLANT(I,2)<245 THEN C2=C2+(SLANT(I,2)-SMEAN2)^2: CNT2=CNT2+1
5190  IF SLANT(I,3)<245 THEN C3=C3+(SLANT(I,3)-SMEAN3)^2: CNT3=CNT3+1
5200 '
5210 NEXT I     ' TEST NEXT SET OF SLANT RNAGES
5220 '
5230 ' LET N1-3 EQUAL THE TOTAL NUMBER OF VALUES-1
5240 N1=CNT1-1: N2=CNT2-1: N3=CNT3-1
5250 '
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5260 ' CALCULATE STANDARD DEVIATIONS
5270 SD1=(C1/N1)^.5: SD2=(C2/N2)^.5: SD3=(C3/N3)^.5
5280 '
5290 ' COMPARE STANDARD DEVIATIONS TO SDLIMIT TO DETERMINE SLANT RANGE
5300 ' ACCEPTABILITY.
5310 '
5320 SDLIMIT=.1     ' SET STANDARD DEVIATION LIMIT
5330 '
5340 IF SD1>SDLIMIT THEN PRINT"DATA OUT OF RANGE - TRY AGAIN.": GOTO 4170
5350 IF SD2>SDLIMIT THEN PRINT"DATA OUT OF RANGE - TRY AGAIN.": GOTO 4170
5360 IF SD3>SDLIMIT THEN PRINT"DATA OUT OF RANGE - TRY AGAIN.": GOTO 4170
5370 '
5380 ' ADD THE COUNTER DELAY EQUIVALENT OF 4.45 CM. TO EACH MEAN SLANT RANGE
5390 SMEAN1=SMEAN1+4.45: SMEAN2=SMEAN2+4.45: SMEAN3=SMEAN3+4.45
5400 '
5410 SP=SGAP+1      ' INCREMENT SRMEAN ARRAY POINTER
5420 '
5430 'STORE MEAN VALUES IN ARRAY SRMEAN(MIKE#,SPARK#)
5440 '
5450 SRMEAN(1,SP)=SMEAN1: SRMEAN(2,SP)=SMEAN2: SRMEAN(3,SP)=SMEAN3
5460 '
5470 NEXT SGAP      ' FIRE NEXT SPARK GAP
5480 '
5490 SFLAG=0        ' RESET SFLAG TO 0
5500 '
5510 RETURN
5520 '
5530 ' SUBROUTINE: NEWTON
5540 '
5550 ' THIS SUBROUTINE SOLVES 3 SETS OF 3 NONLINEAR EQUATIONS FOR 3 UNKNOWNS.
5560 ' USING AN ITERATIVE NEWTON'S METHOD.  DEPENDING ON THE VALUE OF
5570 ' NFLAG, CW1 IS SET TO ZERO OR TO CW SUCH THAT EQUATIONS 6.15 OR 6.13
5580 ' CAN BE SOLVED, RESPECTIVELY.
5590 ' THE OUTPUT IS THE COORDINATES STORED IN ARRAY NSOL.
5600 '
5610 ' INPUTS: FX(POINT,COORD)- FIXED COORDINATES;
5620 '         DIST(POINT,3) - DISTANCES BETWEEN POINTS;
5630 '         CW - COSINE OF ANGLE W, S2-S1-S3 (SPARK GAPS);
5640 '         NFLAG - 1 TO SOLVE EQN. 6.15, 0 TO SOLVE EQN. 6.13
5650 ' OUTPUT: NSOL(POINT,COORD) - COORDINATE SOLUTIONS
5660 ' SUBROUTINE NEEDED: INVERSE
5670 '
5680 ' EVALUATE THE STATUS OF NFLAG AND SET APPROPRIATE VARIABLES.
5690 ' EQNUM - NUMBER OF SETS OF EQUATIONS TO BE SOLVED;
5700 ' INIT - INITIAL VALUES FOR ITERATIVE SOLUTION.
5710 '
5720 IF NFLAG=0 THEN CW1=0: EQNUM=3: INIT=15
5730 IF NFLAG=1 THEN CW1=CW: EQNUM=1: INIT=-30
5740 IF NFLAG=2 THEN CW1=0: EQNUM=1: INIT=10
5750 '
5760 ' SET ITERATIVE TOLERANCE
5770 E=.001
5780 '
5790 ' LOOP THROUGH EACH SET OF EQUATIONS UP TO EQNUM
5800 FOR MK=1 TO EQNUM
5810 '
5820 ' STORE INITIAL SOLUTIONS
5830  FOR COORD=1 TO 3          ' STEP THROUGH X,Y,Z
5840   M#(1,COORD)=ITER         ' STORE INITAL SOLUTION
5850  NEXT COORD                ' NEXT COORDINATE
5860 '
5870 ' LOOP THROUGH UP TO 35 ITERATIONS
5880  FOR ITER=2 TO 35
5890 '
5900 ' STORE ITER-1 SOLUTION
5910   FOR COORD=1 TO 3              ' STEP THROUGH X,Y,Z
```

```
5920     MV#(COORD)=M#(ITER-1,COORD)  ' STORE PREVIOUS SOLUTION
5930    NEXT COORD                    ' NEXT COORDINATE
5940 '
5950 '  CALCULATE JACOBIAN MATRIX COEFFICIENTS FROM THE DERIVATIVES OF THE
5960 '  EQUATIONS.
5970 '
5980    FOR I=1 TO 3
5990     FOR J=1 TO 2
6000      IF J=1 THEN J1=2
6010      IF J=2 THEN J1=1
6020       J#(I,J)=2*(MV#(J)-FX(I,J))+2*CW1*(MV#(J1)-FX(I,J1))
6030     NEXT J
6040     J#(I,3)=2*(MV#(3)-FX(I,3))
6050    NEXT I
6060 '
6070 '  INVERT THE JACOBIAN MATRIX
6080    GOSUB 6420   ' CALL INVERSE
6090 '
6100 '  DETERMINE SOLUTION ITER
6110    FOR I=1 TO 3
6120     F#(I)=(MV#(1)-FX(I,1))^2+(MV#(2)-FX(I,2))^2+(MV#(3)-FX(I,3))^2+2*(MV#(1)
-FX(I,1))*(MV#(2)-FX(I,2))*CW1-DIST(I,MK)
6130    NEXT I
6140 '
6150    FOR I=1 TO 3
6160     M#(ITER,I)=MV#(I)-I#(I,1)*F#(1)-I#(I,2)*F#(2)-I#(I,3)*F#(3)
6170    NEXT I
6180 '
6190 '  CALCULATE ITERATIVE ERROR AND SEE IF IT IS WITHIN THE SET TOLERANCE TOL
6200    FOR I=1 TO 3
6210     T(I)=ABS(M#(ITER,I)-MV#(I))/ABS(M#(ITER,I))
6220    NEXT I
6230 '
6240 '  IF ERROR IS WITHIN TOL STORE SOLUTION OR CONTINUE TO NEXT ITERATION
6250    IF (T(1)<E) AND (T(2)<E) AND (T(3)<E) THEN 6340
6260 '
6270   NEXT ITER      ' NEXT ITERATION
6280 '
6290 '  IF NO SOLUTION IS REACHED AFTER 35 ITERATIONS PRINT ERROR MESSAGE
6300 '  AND STORE LAST ITERATION.
6310   PRINT "NO SOLUTION FOR POINT #";MK: ITER=35
6320 '
6330 '  STORE SOLUTIONS IN ARRAY NSOL
6340   FOR I=1 TO 3
6350    NSOL(MK,I)=M#(ITER,I)
6360   NEXT I
6370 '
6380 NEXT MK        ' NEXT SET OF EQUATIONS
6390 '
6400 RETURN
6410 '
6420 '  FILENAME: INVERSE
6430 '
6440 '  THIS SUBROUTINE INVERTS THE JACOBIAN MATRIX USING THE CROUT ALGORITHM
6450 '
6460 '  INPUT:  J#(3,3) - JACOBIAN MATRIX
6470 '  OUTPUT: I#(3,3) - INVERTED MATRIX
6480 '
6490 '  SET INVERSION CRITEREA BY STORING THE IDENTITY MATRIX SOLUTIONS
6500 FOR I=1 TO 3
6510  FOR J=1 TO 3
6520   IF I=J THEN I#(I,J)=1 ELSE I#(I,J)=0
6530  NEXT J
6540 NEXT I
6550 '
6560 TOL#=1E-09      ' SET ZERO TOLERANCE FOR MATRIX SINGULARITY
```

```
6570 '
6580 FOR I=1 TO 3   ' SEARCH FOR LARGEST ELEMENT IN A COLUMN
6590  X=-1
6600 '
6610  FOR K=1 TO 3   ' SEARCH BELOW MAIN DIAGONAL
6620   IF ABS(J#(K,I))<=X THEN 6640
6630   Q=K: X=ABS(J#(K,I))      ' Q IS ROW OF LARGEST ELEMENT
6640  NEXT K            ' X IS LARGEST ELEMENT
6650 '
6660 ' TEST FOR SINGULAR MATRIX AND STOP IF NECESSARY
6670  IF X>=0 THEN 6690 ELSE PRINT"SINGULAR MATRIX": STOP
6680 '
6690  IF I=Q THEN 6790       'INTERCHANGE IF NEEDED
6700 '
6710  FOR J=1 TO 3       ' NO. SWITCH ROWS I AND Q
6720   T=J#(I,J): J#(I,J)=J#(Q,J): J#(Q,J)=T
6730  NEXT J
6740 '
6750  FOR J=1 TO 3
6760   T=I#(I,J): I#(I,J)=I#(Q,J): I#(Q,J)=T ' SWITCH RIGHT HAND SIDE
6770  NEXT J
6780 '
6790  FOR J=1 TO 3                 ' ELIMINATE ON THAT ONE ROW
6800 '
6810   IF I<J THEN M1=I-1 ELSE M1=J-1
6820   S=0                ' FIND INNER PRODUCT OF ROW I AND COLUMN J  = S
6830 '
6840   FOR K=1 TO M1
6850    S=S+J#(I,K)*J#(K,J)
6860   NEXT K
6870 '
6880   J#(I,J)=J#(I,J)+S
6890 ' STOP HERE IF BELOW MAIN DIAGONAL, CHECK FOR SINGULARITY ELSE NORMALIZE
6900   IF I>=J THEN 6950
6910 '
6920   IF ABS(J#(I,I))<TOL# THEN PRINT"SINGULAR MATRIX": STOP
6930 '
6940   J#(I,J)=-J#(I,J)/J#(I,I)    'ELSE NORMALIZE
6950  NEXT J      ' NEXT COLUMN
6960 NEXT I      ' NEXT COLUMN
6970 '
6980 'REDUCE RIGHT HAND SIDE
6990 '
7000 FOR J=1 TO 3       ' FOR EACH SET OF CONSTANTS
7010  FOR I=1 TO 3      ' LOOK DOWN EACH COLUMN
7020   S=0
7030 '
7040   FOR K=1 TO I-1
7050    S=S+J#(I,K)*I#(K,J) ' TAKE PARTIAL INNER PRODUCT
7060   NEXT K
7070 '
7080   I#(I,J)=-(I#(I,J)+S)/J#(I,I)
7090 '
7100  NEXT I
7110 '
7120  FOR I=3 TO 1 STEP -1   ' WORK BACK UP COLUMN
7130   S=0                   ' TAKE PARTIAL INNER PRODUCTS
7140 '
7150   FOR K=I+1 TO 3
7160    S=S+J#(I,K)*I#(K,J)
7170   NEXT K
7180 '
7190   I#(I,J)=-I#(I,J)+S
7200 '
7210  NEXT I
7220 NEXT J
```

```
7230 '
7240 RETURN
7250 '
7260 ' SUBROUTINE: STORE-SIT
7270 '
7280 ' THIS SUBROUTINE STORES THE OBLIQUE SPARK GAP COORDINATES OF THE FOCAL.
7290 ' NORMAL AND ORIENTATION POINTS IN FILE "SIT".
7300 '
7310 OPEN "SIT" FOR OUTPUT AS #1      ' OPEN FILE SIT TO STORE COORDINATES
7320  FOR PNT=1 TO 3                  ' STEP THROUGH EACH POINT
7330   FOR COORD=1 TO 3               ' STEP THROUGH X,Y,Z
7340    PRINT #1,FOCAL(PNT,COORD)     ' WRITE THE COORDINATE TO THE FILE
7350   NEXT COORD                     ' NEXT COORDINATE
7360  NEXT PNT                        ' NEXT POINT
7370 '
7380 CLOSE #1                         ' CLOSE FILE SIT
7390 '
7400 RETURN
7410 '
7420 ' SUBROUTINE: STORE-SUP
7430 '
7440 ' THIS SUBROUTINE STORES THE OBLIQUE SPARK GAP COORDINATES OF THE FOCAL.
7450 ' NORMAL AND ORIENTATION POINTS IN FILE "SUP".
7460 '
7470 OPEN "SUP" FOR OUTPUT AS #1      ' OPEN FILE SUP TO STORE COORDINATES
7480  FOR PNT=1 TO 3                  ' STEP THROUGH EACH POINT
7490   FOR COORD=1 TO 3               ' STEP THROUGH X,Y,Z
7500    PRINT #1,FOCAL(PNT,COORD)     ' WRITE THE COORDINATE TO THE FILE
7510   NEXT COORD                     ' NEXT COORDINATE
7520  NEXT PNT                        ' NEXT POINT
7530 '
7540 CLOSE #1                         ' CLOSE FILE SUP
7550 '
7560 RETURN
```

```
10 '
20 ' APPENDIX C
30 '
40 ' THESIS TITLE: REFERENCE - DISPLAY SYSTEM FOR THE INTEGRATION OF CT
50 ' SCANNING AND THE OPERATING MICROSCOPE
60 '
70 ' FILENAME: REG
80 '
90 ' PROGRAMMER: JOHN F. HATCH
100 ' DATE: AUGUST, 1984
110 '
120 ' NOTE: REFER TO CHAPTER 6 IN THESIS FOR EQUATIONS,
130 ' AND REFERENCE 10.FOR ALGORITHMS.
140 '
150 ' THIS FILE IS THE DRIVER FOR THE REGISTRATION PROCEDURE.
160 '
170 OPTION BASE 1      ' SET THE LOWER ARRAY INDEX TO 1 FOR CONVENIENCE
180 '
190 ' ALLOCATE SPACE FOR ARRAYS
200 ' NOTE: ARRAY NAMES FOLLOWED BY A "#" SIGN ARE DOUBLE PRECISION
210 '
220 DIM J#(3,3)         ' JACOBIAN MATRIX COEFFICIENTS
230 DIM I#(3,3)         ' JACOBIAN MATRIX INVERSE
240 DIM SRMEAN(3,3)     ' MEAN SLANT RANGES
250 DIM SDATA(3,3,3)    ' SLANT RANGE DATA
260 DIM FOCAL(3,3)      ' FOCAL, NORMAL AND ORIENTATION POINT COORDINATES
270 DIM NSOL(3,3)       ' NEWTON SOLUTIONS
280 DIM FX(3,3)         ' FIXED COORDINATE SYSTEM
290 DIM MV#(3)          ' ITERATION VARIABLE (N-1)
300 DIM M#(100,3)       ' ITERATION VARIABLES
310 DIM SL(3)           ' SLANT RANGE DATA
320 DIM F#(4)           ' ITERATIVE SOLN TO NEWTON
330 DIM DIST(3,3)       ' DISTANCES USED IN NEWTON
340 DIM D(3)            ' DISTANCES USED IN DISTANCE
350 DIM T(3)            ' ITERATION ERRORS
360 DIM MIKE(3,3)       ' MICROPHONE COORDINATES
370 DIM FPOINT(3)       ' FOCAL POINT COORDINATES
380 DIM FPLANE(4)       ' FOCAL PLANE COEFFICIENTS
390 DIM SLANT(150,3)    ' SLANT RANGES
400 '
410 ' MEASURED DISTANCES BETWEEN SPARK GAPS IN CM.
420 S12=30.041        ' SPARK GAP 1 - SPARK GAP 2
430 S23=29.995        ' SPARK GAP 2 - SPARK GAP 3
440 S31=29.657        ' SPARK GAP 3 - SPARK GAP 1
450 '
460 CW=(S12^2+S31^2-S23^2)/(2*S12*S31)    ' COSINE OF ANGLE W, S2-S1-S3 EQ. 6.1
470 S2W=1-CW*CW                           ' SINE SQUARED OF ANGLE W, S2-S1-S3
480 '
490 ' REQUEST OPERATIVE POSITION FOR RIGHT/FRONTAL (R) OR LEFT (L) CRANIOTOMY
500 PRINT
510 PRINT"WHICH OPERATIVE POSITION WILL BE EMPLOYED,"
520 PRINT"    (R) - RIGHT/FRONTAL"
530 PRINT"              OR"
540 PRINT"    (L) - LEFT CRANIOTOMY";
550 INPUT ORPOS$
560 '
570 ' IF "R" THEN IGNORE DATA FROM BLOCKED MIKE 4
580 IF ORPOS$="R" THEN MNOT=4: GOTO 610
590 ' IF "L" THEN IGNORE DATA FROM BLOCKED MIKE 2
600 IF ORPOS$="L" THEN MNOT=2: ELSE GOTO 500
610 '
620 ' REQUEST PATIENT POSITION SITTING (SIT) OR SUPINE (SUP)
630 PRINT
640 PRINT"WHAT POSITION WILL THE PATIENT BE IN,"
650 PRINT"    (SIT) - SITTING"
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660 PRINT"              OR"
670 PRINT"     (SUP)  - SUPINE";
680 INPUT BRACK$
690 '
700 'IF SITTING RECALL FOCAL, NORMAL AND ORIENT. POINT COORDS FROM SITTING FILE
710 IF BRACK$="SIT" THEN GOSUB 7410
720 '
730 'IF SUPINE RECALL FOCAL, NORMAL AND ORIENT. POINT COORDS FROM SUPINE FILE
740 IF BRACK$="SUP" THEN GOSUB 7560 ELSE GOTO 630
750 '
760 PRINT
770 PRINT "TURN ON DIGITIZER AND SPARK GAP MULTIPLEXER."
780 PRINT
790 '
800 ' IF COMPUTER FAILS AFTER REGISTRATION RECALL MICROPHONE COORDINATES
810 PRINT"DID THE COMPUTER FAIL AFTER FOCUSING ON THE FIDUCIALS. YES (Y)"
820 PRINT"OR NO (N)?  ANSWER 'NO' TO THIS QUESTION IF THIS IS THE FIRST TIME"
830 PRINT"RUNNING THIS PROGRAM.";
840 INPUT FAIL$
850 '
860 HFLAG=0
870 IF FAIL$="Y" THEN GOSUB 7720: GOTO 900
880 IF FAIL$<>"N" THEN GOTO 810
890 '
900 CFLAG=0     ' SET CALIBRATION FLAG
910 '
920 PRINT
930 PRINT "DO YOU WANT TO TEST THE REGISTRATION SYSTEM (Y OR N)";
940 INPUT TST$
950 PRINT
960 PRINT"PRESS CTRL BREAK TO STOP AT ANY TIME"
970 PRINT
980 '
990 IF TST$="Y" THEN GOSUB 6650: GOTO 920 ' CALL TEST
1000 IF TST$<>"N" THEN GOTO 920
1010 '
1020 ' DETERMINE MICROPHONE COORDINATES IN CT COORDINATE SYSTEM
1030 '
1040 IF HFLAG=1 THEN GOTO 1080
1050 '
1060 GOSUB 4260     ' CALL REGISTER
1070 '
1080 PRINT
1090 PRINT " BEGIN PROCEDURE - BREAK TO STOP"
1100 PRINT
1110 '
1120 ' STORE MICROPHONE COORDINATES (IN ARRAY MIKE) IN ARRAY FX FOR NEWTON
1130 '
1140 FOR MK=1 TO 3                       ' STEP THROUGH EACH MICROPHONE
1150  FOR COORD=1 TO 3                   ' STEP THROUGH X,Y,Z
1160   FX(MK,COORD)=MIKE(MK,COORD)       ' STORE COORDINATE
1170  NEXT COORD                         ' NEXT COORDINATE
1180 NEXT MK                             ' NEXT MICROPHONE
1190 '
1200 ' LOOP THROUGH UP TO 100 RECONSTRUCTED CT IMAGES
1210 FOR RECON=1 TO 100
1220 '
1230 ' CALL SUBROUTINE SLICE TO TAKE THE COORDINATES OF THE MICROPHONES IN CT
1240 ' COORDINATES AND THE SLANT RANGE DISTANCES AND CALCULATE THE COORDINATES
1250 ' OF THE FOCAL POINT, EQUATION OF THE FOCAL PLANE AND THE THREE DIRECTION
1260 ' COSINES.
1270 '
1280  GOSUB 5260    ' CALL SLICE
1290 '
1300 ' DISPLAY THE COORDINATES OF THE FOCAL POINT, THE EQUATION OF THE FOCAL
1310 ' PLANE AND THE THREE DIRECTION COSINES.
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```
1320 '
1330  PRINT
1340  PRINT"FOCAL POINT COORDINATES (X,Y,Z)"
1350  PRINT
1360  PRINT FPOINT(1),FPOINT(2),FPOINT(3)
1370  PRINT
1380  PRINT"FOCAL PLANE COEFFICIENTS (A,B,C,D)"
1390  PRINT
1400  PRINT FPLANE(1),FPLANE(2),FPLANE(3),FPLANE(4)
1410  PRINT
1420  PRINT"X DIRECTION COSINE=";DCOSX
1430  PRINT"Y DIRECTION COSINE=";DCOSY
1440  PRINT"Z DIRECTION COSINE=";DCOSZ
1450 '
1460 NEXT RECON       ' REFOCUS FOR NEXT SLICE
1470 '
1480 ' STOP AFTER 100 RECONSTRUCTED CT IMAGES
1490 '
1500 STOP
1510 '
1520 ' SUBROUTINE: SRINP
1530 '
1540 ' THIS FILE OPENS THE RS-232 PORT FOR DIGITIZER COMMUNICATIONS,
1550 ' CONTROLS THE SPARK GAP MULTIPLEXER, STORES THE SLANT RANGES
1560 ' IN AN ARRAY, AND DETERMINES THE STANDARD DEVIATIONS AND MEANS.
1570 '
1580 ' INPUT: MNOT - IGNORED MICROPHONE
1590 ' OUTPUT: SRMEAN(MIKE,SKGAP) - AVERAGE SLANT RANGES FOR EACH SPARK GAP
1600 '
1610 PRINT
1620 PRINT "*****PRESS ANY KEY WHEN FOCUSED/READY*****"
1630 PRINT
1640 '
1650 ' PAUSE UNTIL ANY KEY IS DEPRESSED
1660 P$=INKEY$: IF P$="" THEN 1660
1670 '
1680 FOR SGAP=0 TO 2  ' SET MULTIPLEXER THROUGH PARALLEL PORT
1690 ' CHANGE SGAP TO SGAP1 FOR PROPER MULTIPLEXER SEQUENCING
1700  IF SGAP=0 THEN SGAP1=0
1710  IF SGAP=1 THEN SGAP1=2
1720  IF SGAP=2 THEN SGAP1=1
1730 '
1740 ' WRITE THE BINARY CODE FOR SGAP1 TO THE PARALLEL PORT ADDRESS 3BC HEX
1750  OUT &H3BC,SGAP1
1760 '
1770 ' OPEN RS-232 PORT, SET BAUD RATE AND PARITY
1780  OPEN "COM1:9600,O,7,1" AS #1
1790 '
1800   FLAG=1          ' INITIALIZE CHARACTER FLAG
1810   WHILE FLAG      ' SEARCH CHARACTER INPUT FOR ASCII LINE FEED IF FLAG=1
1820    S$=INPUT$(1,#1)
1830     IF ASC(S$)=10 THEN FLAG=0 ELSE FLAG=1
1840   WEND
1850 '
1860  W$=INPUT$(26,#1)    ' IGNORE FIRST VALUES (FROM LAST SLANT RANGES)
1870 '
1880  FOR I=1 TO 30       ' FIRE EACH SPARK GAP 30 TIMES
1890 '
1900 ' MONITOR COMM. BUFFER, IF >40 CHARACTERS IN BUFFER TURN OFF DIGITIZER
1910 ' BY WRITING BINARY CODE 10 TO ADDRESS 3FC HEX - THE RS-232 PORT
1920 '
1930   IF LOC(1)>40 THEN OUT &H3FC,10 ELSE OUT &H3FC,11
1940 '
1950 ' INPUT SLANT RANGES AND INSERT DECIMAL POINTS TO READ DISTANCES IN CM.
1960 '
1970   A$=INPUT$(26,#1)     ' INPUT 26 CHARACTER STRING (4 SLANT RANGES)
```

```
1980 '
1990  C$=MID$(A$,1,6): CL$=LEFT$(C$,3): CR$=RIGHT$(C$,3): CC$=CL$+"."+CR$
2000  D$=MID$(A$,7,6): DL$=LEFT$(D$,3): DR$=RIGHT$(D$,3): DD$=DL$+"."+DR$
2010  E$=MID$(A$,13,6): EL$=LEFT$(E$,3): ER$=RIGHT$(E$,3): EE$=EL$+"."+ER$
2020  F$=MID$(A$,19,6): FL$=LEFT$(F$,3): FR$=RIGHT$(F$,3): FF$=FL$+"."+FR$
2030 '
2040 ' STORE THE VALUE OF EACH CHARACTER STRING FOR EACH SLANT RANGE IN G1-4
2050  G1=VAL(CC$): G2=VAL(DD$): G3=VAL(EE$): G4=VAL(FF$)
2060 '
2070 ' IGNORE SLANT RANGE DATA FROM MICROPHONE MNOT AND STORE REMAINING
2080 ' SLANT RANGES IN P1-3
2090 '
2100  IF MNOT=1 THEN P1=G2: P2=G4: P3=G3
2110  IF MNOT=2 THEN P1=G1: P2=G3: P3=G4
2120  IF MNOT=3 THEN P1=G4: P2=G2: P3=G1
2130  IF MNOT=4 THEN P1=G3: P2=G1: P3=G2
2140 '
2150 ' STORE SLANT RANGES IN ARRAY SLANT
2160  SLANT(I,1)=P1: SLANT(I,2)=P2: SLANT(I,3)=P3
2170 '
2180 NEXT I     ' GET NEXT SET OF FOUR SLANT RANGES
2190 '
2200 CLOSE #1    ' SUPPRESS DIGITIZER COMMUNICATION
2210 '
2220 ' CALCULATE MEAN SLANT RANGE VALUES
2230 '
2240 C1=0: C2=0: C3=0                 ' INITIALIZE SLANT RANGE SUM
2250 BAD1=0: BAD2=0: BAD3=0           ' INITIALIZE BAD DATA COUNTER
2260 CNT1=0: CNT2=0: CNT3=0           ' INITIALIZE NUMBER OF SLANT RANGES
2270 '
2280 FOR I=1 TO 30                    ' STEP THROUGH EACH SLANT RANGE
2290 '
2300 ' TEST EACH SLANT RANGE, IF LESS THAN MAX VALUE OF 245 CM. ADD TO SUM.
2310 ' IF A VALUE IS GREATER THAN 245 CM., INCREMENT BAD COUNTER AND IGNORE
2320 ' THE BAD DATA.  IF 5 BAD VALUES ARE DETECTED, THE MICROPHONE IN ERROR
2330 ' MIGHT BE BLOCKED, AN ERROR MESSAGE IS DISPLAYED AND SRINP IS RECALLED.
2340 '
2350  IF SLANT(I,1)<245 THEN C1=C1+SLANT(I,1): CNT1=CNT1+1: ELSE BAD1=BAD1+1
2360 '
2370  IF BAD1>=5 THEN PRINT "BAD DATA FROM X MIKE-TRY AGAIN.": GOTO 1620
2380 '
2390  IF SLANT(I,2)<245 THEN C2=C2+SLANT(I,2): CNT2=CNT2+1: ELSE BAD2=BAD2+1
2400 '
2410  IF BAD2>=5 THEN PRINT "BAD DATA FROM ZERO MIKE-TRY AGAIN.": GOTO 1620
2420 '
2430  IF SLANT(I,3)<245 THEN C3=C3+SLANT(I,3): CNT3=CNT3+1: ELSE BAD3=BAD3+1
2440 '
2450  IF BAD3>=5 THEN PRINT "BAD DATA FROM Y MIKE-TRY AGAIN.": GOTO 1620
2460 '
2470 NEXT I    ' TEST NEXT SET OF SLANT RNAGES
2480 '
2490 ' CALCULATE THE AVERAGE SLANT RANGE VALUES
2500 SMEAN1=C1/CNT1: SMEAN2=C2/CNT2: SMEAN3=C3/CNT3
2510 '
2520 ' CALCULATE STANDARD DEVIATIONS OF SLANT RANGE VALUES TO DETERMINE IF
2530 ' THERE IS UNACCEPTABLE VARIATION IN THE DATA, IE. A AIR DISTURBANCE.
2540 '
2550 C1=0: C2=0: C3=0                 ' INITIALIZE SLANT RANGE SUM
2560 CNT1=0: CNT2=0: CNT3=0           ' INITIALIZE NUMBER OF SLANT RANGES
2570 '
2580 FOR I=1 TO 30                    ' STEP THROUGH EACH SLANT RANGE
2590 '
2600  IF SLANT(I,1)<245 THEN C1=C1+(SLANT(I,1)-SMEAN1)^2: CNT1=CNT1+1
2610  IF SLANT(I,2)<245 THEN C2=C2+(SLANT(I,2)-SMEAN2)^2: CNT2=CNT2+1
2620  IF SLANT(I,3)<245 THEN C3=C3+(SLANT(I,3)-SMEAN3)^2: CNT3=CNT3+1
2630 '
```

```
2640 NEXT I     ' TEST NEXT SET OF SLANT RNAGES
2650 '
2660 ' LET N1-3 EQUAL THE TOTAL NUMBER OF VALUES-1
2670 N1=CNT1-1: N2=CNT2-1: N3=CNT3-1
2680 '
2690 ' CALCULATE STANDARD DEVIATIONS
2700 SD1=(C1/N1)^.5: SD2=(C2/N2)^.5: SD3=(C3/N3)^.5
2710 '
2720 ' COMPARE STANDARD DEVIATIONS TO SDLIMIT TO DETERMINE SLANT RANGE
2730 ' ACCEPTABILITY.
2740 '
2750 SDLIMIT=.1     ' SET STANDARD DEVIATION LIMIT
2760 '
2770 IF SD1>SDLIMIT THEN PRINT"DATA OUT OF RANGE - TRY AGAIN.": GOTO 1620
2780 IF SD2>SDLIMIT THEN PRINT"DATA OUT OF RANGE - TRY AGAIN.": GOTO 1620
2790 IF SD3>SDLIMIT THEN PRINT"DATA OUT OF RANGE - TRY AGAIN.": GOTO 1620
2800 '
2810 ' ADD THE COUNTER DELAY EQUIVALENT OF 4.45 CM. TO EACH MEAN SLANT RANGE
2820 SMEAN1=SMEAN1+4.45: SMEAN2=SMEAN2+4.45: SMEAN3=SMEAN3+4.45
2830 '
2840 SP=SGAP+1      ' INCREMENT SRMEAN ARRAY POINTER
2850 '
2860 'STORE MEAN VALUES IN ARRAY SRMEAN(MIKE#,SPARK#)
2870 '
2880 SRMEAN(1,SP)=SMEAN1: SRMEAN(2,SP)=SMEAN2: SRMEAN(3,SP)=SMEAN3
2890 '
2900 NEXT SGAP      ' FIRE NEXT SPARK GAP
2910 '
2920 RETURN
2930 '
2940 ' SUBROUTINE: DISTANCE
2950 '
2960 ' THIS SUBROUTINE DETERMINES THE DISTANCE BETWEEN TWO POINTS IN OBLIQUE
2970 ' SPARK GAP COORDINATES.
2980 '
2990 ' INPUTS: FOCAL(POINT,COORD) - OBLIQUE SPARK GAP COORDINATES OF FOCAL,
3000 '         NORMAL AND ORIENTATION POINTS;
3010 '         SL(POINT) - SLANT RANGE DISTANCES FOR EACH POINT;
3020 '         CW - COSINE OF ANGLE W, S2-S1-S3 (SPARK GAPS);
3030 '         S2W - SINE OF ANGLE W SQUARED
3040 '         PFLAG - FLAG TO INDICATE REGISTRATION PROCEDURE
3050 ' OUTPUT: D(POINT) - DISTANCES FROM FOCAL, NORMAL AND ORIENTATION POINTS
3060 '
3070 ' POINT 1
3080 ' CALCULATE PROJECTIONS OF SLANT 1 ON X AND Y SPARK AXES
3090 '
3100 XP1=(SL(1)^2+S31^2-SL(3)^2)/(2*S31)     ' EQN. 6.3
3110 YP1=(SL(1)^2+S12^2-SL(2)^2)/(2*S12)     ' EQN. 6.4
3120 '
3130 ' CALCULATE OBLIQUE COORDINATES OF POINT 1
3140 '
3150 X1=(XP1-YP1*CW)/S2W                     ' EQN. 6.8
3160 Y1=(YP1-XP1*CW)/S2W                     ' EQN. 6.9
3170 Z1=(SL(1)^2-X1^2-Y1^2-2*X1*Y1*CW)^.5    ' EQN. 6.12
3180 '
3190 ' POINT 2
3200 '
3210 ' FOR REGISTRATION PROCEDURE, ONLY THE FOCAL POINT IS NEEDED SO
3220 ' PTS=1.  THIS IS DETERMINED BY PFLAG.
3230 '
3240 IF PFLAG=1 THEN PTS=1 ELSE PTS=3
3250 '
3260 FOR I=1 TO PTS   ' STEP THROUGH FOCAL, NORMAL AND ORIENT. POINT COORDS.
3270 '
3280 ' RECALL FOCAL, NORMAL AND ORIENTATION POINT COORDINATES
3290 '
```

```
3300 X2=FOCAL(I,1)
3310 Y2=FOCAL(I,2)
3320 Z2=FOCAL(I,3)
3330 '
3340 ' CALCULATE DISTANCE D USING OBLIQUE DISTANCE FORMULA, EQN. 6.14
3350 '
3360 D(I)=(X2-X1)^2+(Y2-Y1)^2+(Z2-Z1)^2+2*(X2-X1)*(Y2-Y1)*CW
3370 '
3380 NEXT I
3390 '
3400 RETURN
3410 '
3420 ' FILENAME: INVERSE
3430 '
3440 ' THIS SUBROUTINE INVERTS THE JACOBIAN MATRIX USING THE CROUT ALGORITHM
3450 '
3460 ' INPUT: J#(3,3) - JACOBIAN MATRIX
3470 ' OUTPUT: I#(3,3) - INVERTED MATRIX
3480 '
3490 ' SET INVERSION CRITEREA BY STORING THE IDENTITY MATRIX SOLUTIONS
3500 FOR I=1 TO 3
3510  FOR J=1 TO 3
3520   IF I=J THEN I#(I,J)=1 ELSE I#(I,J)=0
3530  NEXT J
3540 NEXT I
3550 '
3560 TOL#=1E-09      ' SET ZERO TOLERANCE FOR MATRIX SINGULARITY
3570 '
3580 FOR I=1 TO 3    ' SEARCH FOR LARGEST ELEMENT IN A COLUMN
3590  X=-1
3600 '
3610  FOR K=1 TO 3    ' SEARCH BELOW MAIN DIAGONAL
3620   IF ABS(J#(K,I))<=X THEN 3640
3630   Q=K: X=ABS(J#(K,I))     ' Q IS ROW OF LARGEST ELEMENT
3640  NEXT K              ' X IS LARGEST ELEMENT
3650 '
3660 ' TEST FOR SINGULAR MATRIX AND STOP IF NECESSARY
3670  IF X>=0 THEN 3690 ELSE PRINT"SINGULAR MATRIX": STOP
3680 '
3690  IF I=Q THEN 3790      'INTERCHANGE IF NEEDED
3700 '
3710  FOR J=1 TO 3        ' NO. SWITCH ROWS I AND Q
3720   T=J#(I,J): J#(I,J)=J#(Q,J): J#(Q,J)=T
3730  NEXT J
3740 '
3750  FOR J=1 TO 3
3760   T=I#(I,J): I#(I,J)=I#(Q,J): I#(Q,J)=T ' SWITCH RIGHT HAND SIDE
3770  NEXT J
3780 '
3790  FOR J=1 TO 3                ' ELIMINATE ON THAT ONE ROW
3800 '
3810   IF I<J THEN M1=I-1 ELSE M1=J-1
3820   S=0               ' FIND INNER PRODUCT OF ROW I AND COLUMN J  = S
3830 '
3840   FOR K=1 TO M1
3850    S=S+J#(I,K)*J#(K,J)
3860   NEXT K
3870 '
3880   J#(I,J)=J#(I,J)+S
3890 ' STOP HERE IF BELOW MAIN DIAGONAL, CHECK FOR SINGULARITY ELSE NORMALIZE
3900   IF I>=J THEN 3950
3910 '
3920   IF ABS(J#(I,I))<TOL# THEN PRINT"SINGULAR MATRIX": STOP
3930 '
3940   J#(I,J)=-J#(I,J)/J#(I,I)    'ELSE NORMALIZE
3950  NEXT J     ' NEXT COLUMN
```

```
3960 NEXT I      ' NEXT COLUMN
3970 '
3980 'REDUCE RIGHT HAND SIDE
3990 '
4000 FOR J=1 TO 3        ' FOR EACH SET OF CONSTANTS
4010  FOR I=1 TO 3       ' LOOK DOWN EACH COLUMN
4020   S=0
4030 '
4040   FOR K=1 TO I-1
4050    S=S+J#(I,K)*I#(K,J) ' TAKE PARTIAL INNER PRODUCT
4060   NEXT K
4070 '
4080   I#(I,J)=-(I#(I,J)+S)/J#(I,I)
4090 '
4100  NEXT I
4110 '
4120  FOR I=3 TO 1 STEP -1   ' WORK BACK UP COLUMN
4130   S=0                   ' TAKE PARTIAL INNER PRODUCTS
4140 '
4150   FOR K=I+1 TO 3
4160    S=S+J#(I,K)*I#(K,J)
4170   NEXT K
4180 '
4190  I#(I,J)=-I#(I,J)+S
4200 '
4210  NEXT I
4220 NEXT J
4230 '
4240 RETURN
4250 '
4260 ' SUBROUTINE: REGISTER
4270 '
4280 ' THIS SUBROUTINE CALCULATES THE COORDINATES OF THE THREE MICROPHONES
4290 ' IN THE CT COORDINATE SYSTEM AND STORES THEM IN FILE MIKE.
4300 '
4310 ' INPUT: FOCAL(1,COORD) - OBLIQUE SPARK GAP COORDINATES OF FOCAL POINT
4320 ' OUTPUT: MIKE(MK,AX) - CT COORDINATES OF MICROPHONES
4330 ' SUBROUTINES NEEDED: SRINP, NEWTON
4340 '
4350 PFLAG=1     ' SET FOCAL POINT ONLY FLAG FOR SUBROUTINE DISTANCE
4360 '
4370 ' COLLECT FIDUCIAL DATA
4380 '
4390 FOR FID=1 TO 3              ' STEP THROUGH EACH FIDUCIAL
4400  PRINT
4410  PRINT "FOCUS ON FIDUCIAL POINT #";FID
4420 '
4430 ' CALL SUBROUTINE SRINP TO COLLECT SLANT RANGE DISTANCES
4440 '
4450   GOSUB 1520  ' CALL SRINP
4460 '
4470   ' STORE AVERAGE SLANT RANGE DATA IN ARRAY SDATA
4480   FOR MK=1 TO 3             ' STEP THROUGH EACH MICROPHONE
4490    FOR SPK=1 TO 3           ' STEP THROUGH EACH SPARK GAP
4500     SDATA(FID,MK,SPK)=SRMEAN(MK,SPK) ' STORE SLANT RANGE DATA
4510    NEXT SPK                 ' NEXT SPARK GAP
4520   NEXT MK                   ' NEXT MICROPHONE
4530 NEXT FID                    ' NEXT FIDUCIAL
4540 '
4550 PRINT
4560 PRINT"CALCULATING MICROPHONE COORDINATES..."
4570 PRINT
4580 ' CALCULATE DISTANCES BETWEEN MICROPHONES AND FIDUCIALS
4590 '
4600 FOR FID=1 TO 3                    ' STEP THROUGH EACH FIDUCIAL
4610  FOR MK=1 TO 3                    ' STEP THROUGH EACH MICROPHONE
```

```
4620   FOR SPK=1 TO 3                    ' STEP THROUGH EACH SPARK GAP
4630    SL(SPK)=SDATA(FID,MK,SPK)        ' STORE SLANT RANGE DATA IN VECTOR SL
4640   NEXT SPK                          ' NEXT SPARK GAP
4650 '
4660 ' CALCULATE THE DISTANCES BETWEEN THE FIDUCIALS (FOCAL POINT) AND THE
4670 ' MICROPHONES.
4680 '
4690   GOSUB 2940   ' CALL DISTANCE
4700 '
4710 ' STORE DISTANCES TO FOCAL POINT IN ARRAY DIST
4720 '
4730   DIST(FID,MK)=D(1)
4740 '
4750  NEXT MK                            ' NEXT MICROPHONE
4760 NEXT FID                            ' NEXT FIDUCIAL
4770 '
4780 ' IF TESTING THE REGISTRATION PROCEDURE, FIDUCIAL COORDINATES ARE
4790 ' KNOWN SO DO NOT ENTER COORDINATES.
4800 '
4810 IF CFLAG=1 THEN 4990
4820 '
4830 ' ENTER FIDUCIAL COORDINATES
4840 '
4850 PRINT
4860 PRINT "ENTER CT COORDINATES OF THE FIDUCIALS"
4870 '
4880 FOR FID=1 TO 3              ' STEP THROUGH EACH FIDUCIAL
4890 '
4900  PRINT
4910  PRINT"FIDUCIAL #";FID;"X, Y, Z";
4920 '
4930 ' STORE FIDUCIAL COORDINATES IN ARRAY FX
4940 '
4950  INPUT FX(FID,1),FX(FID,2),FX(FID,3)
4960 '
4970 NEXT FID                    ' NEXT FIDUCIAL
4980 '
4990 ' CALCULATE MICROPHONE COORDINATES BY SOLVING THREE NONLINEAR EQUATIONS
5000 ' FOR THREE UNKNOWNS USING NEWTONS METHOD.  EQN. 6.15.
5010 '
5020 GOSUB 5910    ' CALL NEWTON
5030 '
5040 ' STORE MICROPHONE COORDINATES IN ARRAY MIKE
5050 '
5060 FOR MK=1 TO 3                       ' STEP THROUGH EACH MICROPHONE
5070  FOR COORD=1 TO 3                   ' STEP THROUGH X,Y,Z
5080   MIKE(MK,COORD)=NSOL(MK,COORD)     ' STORE COORDINATE
5090  NEXT COORD                         ' NEXT COORDINATE
5100 NEXT MK                             ' NEXT MICROPHONE
5110 '
5120 ' STORE CT COORDINATES OF MICROPHONES IN FILE MIKE
5130 '
5140 OPEN "MIKE" FOR OUTPUT AS #1 ' OPEN FILE MIKE FOR OUTPUT
5150  FOR MK=1 TO 3                ' LOOP THROUGH EACH MICROPHONE
5160   FOR COORD=1 TO 3            ' LOOP THROUGH X, Y AND Z
5170    PRINT #1,MIKE(MK,COORD)    ' WRITE EACH VALUE TO THE FILE
5180   NEXT COORD
5190  NEXT MK
5200 CLOSE #1                      ' CLOSE THE FILE
5210 '
5220 PFLAG=0                       ' RESET FOCAL POINT COORDINATE FLAG
5230 '
5240 RETURN
5250 '
5260 ' SUBROUTINE: SLICE
5270 '
```

```
5280 ' THIS SUBROUTINE CALCULATES THE CT COORDINATES OF THE FOCAL, NORMAL AND
5290 ' ORIENTATION POINTS TO DEFINE THE FOCAL PLANE.  IT ALSO DETERMINES
5300 ' THE FOCAL PLANE COEFFICIENTS AND THE THREE DIRECTION COSINES.
5310 '
5320 ' INPUTS: MIKE(MK,AX) - CT COORDINATES OF MICROPHONES;
5330 '         FOCAL(POINT,COORD) - OBLIQUE SPARK GAP COORDINATES OF THE FOCAL,
5340 '         NORMAL AND ORIENTATION POINTS.
5350 ' OUTPUTS: FPOINT(COORD) - FOCAL POINT COORDINATES;
5360 '          FPLANE(COEFF) - FOCAL PLANE COEFFICIENTS;
5370 '          DCOSX - X DIRECTION COSINE OF THE FOCAL - ORIENT. POINT VECTOR
5380 '          DCOSY - Y DIRECTION COSINE OF THE FOCAL - ORIENT. POINT VECTOR
5390 '          DCOSZ - Z DIRECTION COSINE OF THE FOCAL - ORIENT. POINT VECTOR
5400 ' SUBROUTINES NEEDED: SRINP, NEWTON
5410 '
5420 ' GET SLANT RANGES
5430 '
5440 GOSUB 1520    ' CALL SRINP
5450 '
5460 FOR MK=1 TO 3                  ' STEP THROUGH EACH MICROPHONE
5470  FOR SPK=1 TO 3                ' STEP THROUGH EACH SPARK GAP
5480 ' STORE SLANT RANGE DATA IN VECTOR SL
5490   SL(SPK)=SRMEAN(MK,SPK)
5500  NEXT SPK                      ' NEXT SPARK GAP
5510 '
5520  GOSUB 2940 ' CALL DISTANCE
5530 '
5540  FOR PT=1 TO 3                 ' STEP THROUGH EACH POINT
5550 ' STORE DISTANCES IN ARRAY
5560    DIST(MK,PT)=D(PT)
5570  NEXT PT                       ' NEXT POINT
5580 NEXT MK                        ' NEXT MICROPHONE
5590 '
5600 GOSUB 5920   ' CALL NEWTON - EQN. 6.28
5610 '
5620 ' STORE FOCAL POINT COORDINATES
5630 FOR COORD=1 TO 3     ' STEP THROUGH X,Y,Z
5640  FPOINT(COORD)=NSOL(1,COORD)
5650 NEXT COORD           ' NEXT COORDINATE
5660 '
5670 FOR I=1 TO 3      ' CALCULATE AND STORE FOCAL PLANE COEFFICIENTS
5680  FPLANE(I)=NSOL(2,I)-FPOINT(I)
5690 NEXT I
5700 '
5710 FPLANE(4)=0
5720 FOR I=1 TO 3      ' STEP THROUGH EACH COEFFICIENT
5730  FPLANE(4)=FPLANE(4)+FPLANE(I)*FPOINT(I)
5740 NEXT I            ' NEXT COEFFICIENT
5750 '
5760 ' CALCULATE AND STORE X, Y AND Z DIRECTION COSINES
5770 '
5780 NORMAL=0          ' INITIALIZE VECTOR NORM
5790 '
5800 FOR COORD=1 TO 3     ' STEP THROUGH X,Y,Z
5810  NORM=NORM+(NSOL(3,COORD)-NSOL(1,COORD))^2    ' EQN. 6.29
5820 NEXT COORD           ' NEXT COORDINATE
5830 '
5840 NORM=NORM^.5
5850 '
5860 DCOSX=(NSOL(3,1)-NSOL(1,1))/NORM    ' EQN. 6.30
5870 DCOSY=(NSOL(3,2)-NSOL(1,2))/NORM    ' EQN. 6.31
5880 DCOSZ=(NSOL(3,3)-NSOL(1,3))/NORM    ' EQN. 6.32
5890 '
5900 RETURN
5910 '
5920 ' SUBROUTINE: NEWTON
5930 '
```

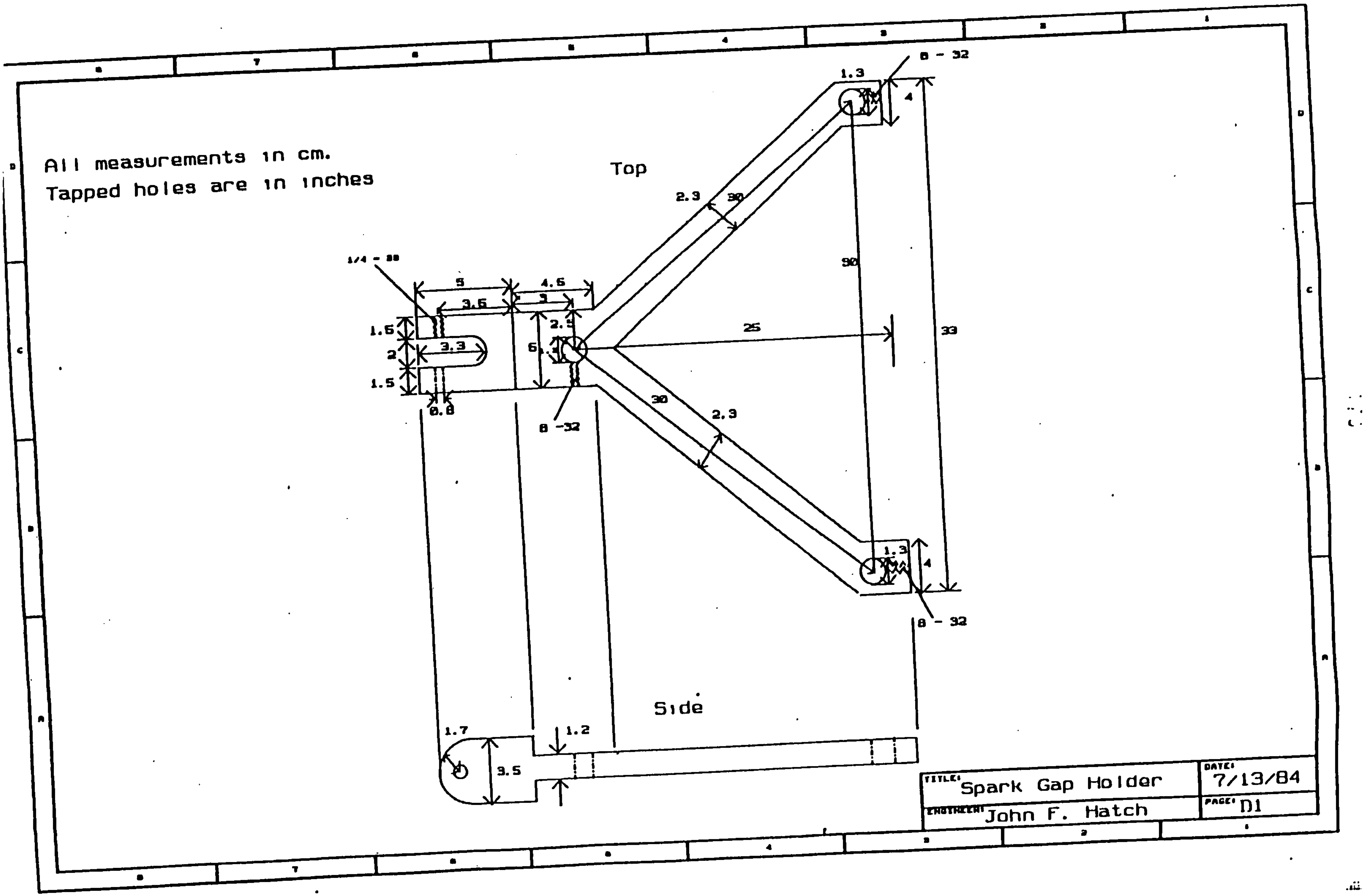
```
5940 ' THIS SUBROUTINE SOLVES 3 SETS OF 3 NONLINEAR EQUATIONS FOR 3 UNKNOWNS.
5950 ' USING AN ITERATIVE NEWTON'S METHOD.  THE EQUATIONS ARE IN THE FORM OF
5960 ' DIST=((FX1-NSOL1)^2+(FX2-NSOL2)^2+(FX3-NSOL3)^2)^.5, WHERE DIST AND FX
5970 ' ARE KNOWN AND NSOL IS UNKNOWN.
5980 '
5990 ' INPUTS: FX(POINT,COORD)- FIXED COORDINATES;
6000 '         DIST(POINT,3) - DISTANCES BETWEEN POINTS;
6010 '         CW - COSINE OF ANGLE W, S2-S1-S3 (SPARK GAPS)
6020 ' OUTPUT: NSOL(POINT,COORD) - COORDINATE SOLUTIONS
6030 ' SUBROUTINE NEEDED: INVERSE
6040 '
6050 ' SET CONSTANTS
6060 E=.001     ' ITERATIVE TOLERANCE
6070 ' LOOP THROUGH EACH SET OF EQUATIONS
6080 FOR MK=1 TO 3
6090 '
6100 ' STORE INITIAL SOLUTIONS
6110  FOR PT=1 TO 3
6120   M#(1,PT)=15
6130  NEXT PT
6140 '
6150 ' LOOP THROUGH UP TO 35 ITERATIONS
6160  FOR ITER=2 TO 35
6170 '
6180 ' STORE ITER-1 SOLUTION
6190   FOR PT=1 TO 3
6200    MV#(PT)=M#(ITER-1,PT)
6210   NEXT PT
6220 '
6230 ' CALCULATE JACOBIAN MATRIX COEFFICIENTS FROM THE DERIVATIVES OF THE
6240 ' EQUATIONS.
6250   FOR I=1 TO 3
6260    FOR J=1 TO 3
6270     J#(I,J)=2*(MV#(J)-FX(I,J))
6280    NEXT J
6290   NEXT I
6300 '
6310 ' INVERT THE JACOBIAN MATRIX
6320   GOSUB 3420   ' CALL INVERSE
6330 '
6340 ' DETERMINE SOLUTION ITER
6350   FOR I=1 TO 3
6360    F#(I)=(MV#(1)-FX(I,1))^2+(MV#(2)-FX(I,2))^2+(MV#(3)-FX(I,3))^2-DIST(I,MK
6370   NEXT I
6380 '
6390   FOR I=1 TO 3
6400    M#(ITER,I)=MV#(I)-I#(I,1)*F#(1)-I#(I,2)*F#(2)-I#(I,3)*F#(3)
6410   NEXT I
6420 '
6430 ' CALCULATE ITERATIVE ERROR AND SEE IF IT IS WITHIN THE SET TOLERANCE TOL
6440   FOR I=1 TO 3
6450    T(I)=ABS(M#(ITER,I)-MV#(I))/ABS(M#(ITER,I))
6460   NEXT I
6470 '
6480 ' IF ERROR IS WITHIN TOL STORE SOLUTION OR CONTINUE TO NEXT ITERATION
6490   IF (T(1)<E) AND (T(2)<E) AND (T(3)<E) THEN 6580
6500 '
6510  NEXT ITER     ' NEXT ITERATION
6520 '
6530 ' IF NO SOLUTION IS REACHED AFTER 35 ITERATIONS PRINT ERROR MESSAGE
6540 ' AND STORE LAST ITERATION.
6550  PRINT "NO SOLUTION FOR POINT #";MK: ITER=35
6560 '
6570 ' STORE SOLUTIONS IN ARRAY NSOL
6580  FOR I=1 TO 3
```

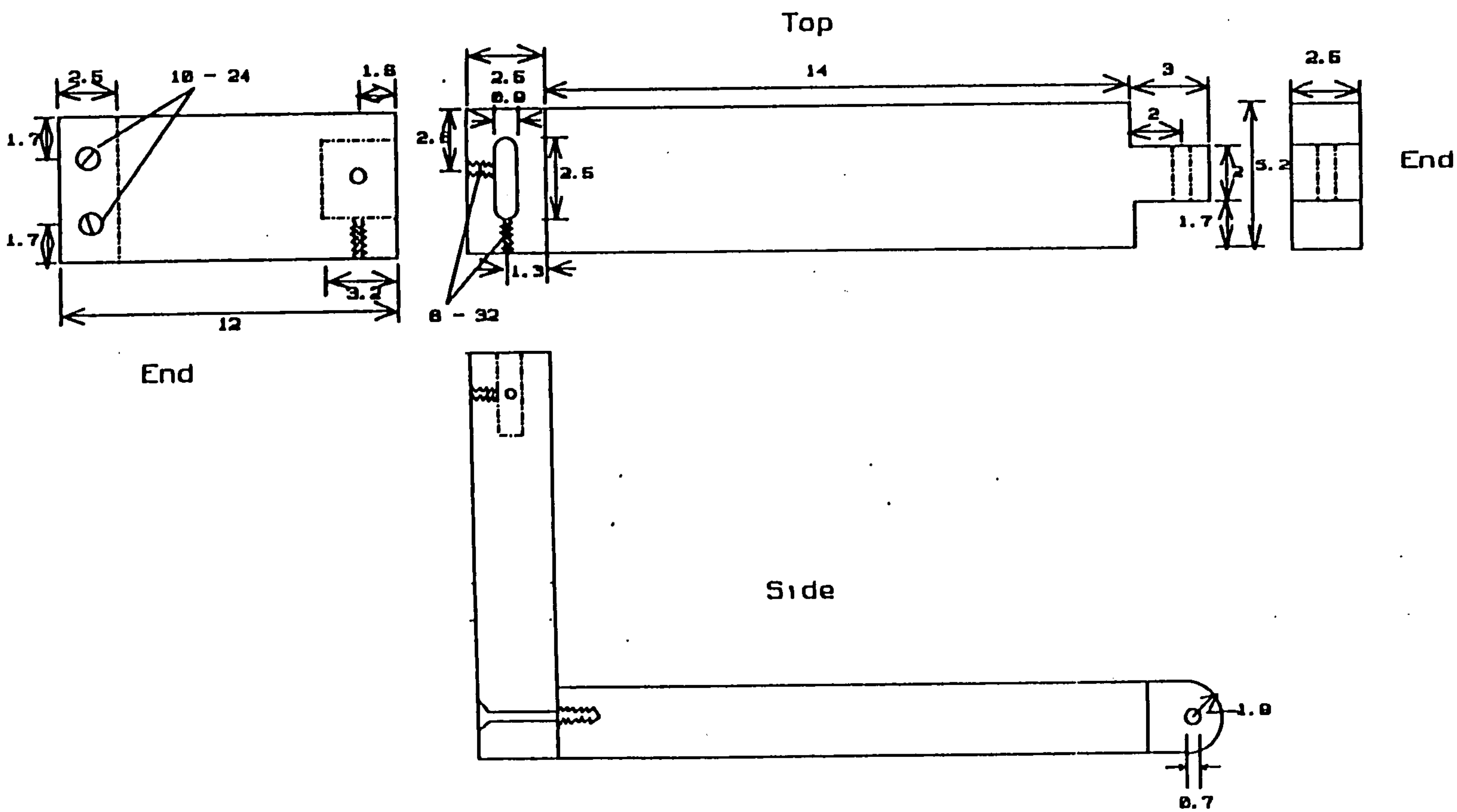
```
6590   NSOL(MK,I)=M#(ITER,I)
6600  NEXT I
6610 '
6620 NEXT MK       ' NEXT SET OF EQUATIONS
6630 '
6640 RETURN
6650 '
6660 ' SUBROUTINE: TEST
6670 '
6680 ' THIS SUBROUTINE IS USED TO TEST THE REFERENCE SYSTEM AND REQUIRES
6690 ' THE TEST PHANTOM WHOSE FIDUCIAL COORDINATES AND TEST POINTS ARE KNOWN.
6700 ' THE OUTPUT OF THE SUBROUTINE INCLUDES THE COORDINATES OF THE FOCAL
6710 ' POINT, THE FOCAL PLANE COEFFICIENTS, THE DIRECTION COSINES OF THE
6720 ' FOCAL - ORIENTATION POINT VECTOR AND THE ABSOLUTE ERROR AT THE FOCAL
6730 ' POINT.
6740 '
6750 ' SUBROUTINES NEEDED: REGISTER, SLICE
6760 '
6770 IF HFLAG=1 GOTO 6920
6780 PRINT
6790 PRINT"ANCHOR THE TEST PHANTOM BLOCK WITH RESPECT TO THE MICROPHONES."
6800 PRINT
6810 '
6820 ' STORE FIDUCIAL COORDINATES
6830 FX(1,1)=0: FX(1,2)=0: FX(1,3)=0
6840 FX(2,1)=-1.671: FX(2,2)=7.62: FX(2,3)=4.854
6850 FX(3,1)=1.016: FX(3,2)=15.867: FX(3,3)=-1.75
6860 '
6870 ' SET CALIBRATION FLAG FOR SUBROUTINE DISTANCE
6880 CFLAG=1
6890 '
6900 GOSUB 4260 ' CALL REGISTER-DETERMINE MICROPHONE COORDINATES
6910 '
6920 FOR I=1 TO 3 ' STORE MICROPHONE COORDINATES IN ARRAY FX FOR NEWTON
6930  FOR J=1 TO 3
6940   FX(I,J)=MIKE(I,J)
6950  NEXT J
6960 NEXT I
6970 '
6980 ' LOOP THROUGH UP TO 100 TEST POINTS
6990 FOR TPOINT=1 TO 100
7000 '
7010  PRINT "ENTER TEST POINT # (1-5) OR FIDUCIAL # (F1-F3)";
7020  INPUT TPT$
7030 '
7040 ' LOOK UP KNOWN COORDINATES OF TEST POINT
7050  IF TPT$="1" THEN TX=-4.719: TY=7.62: TZ=.79: GOTO 7150
7060  IF TPT$="2" THEN TX=2.54: TY=0: TZ=0: GOTO 7150
7070  IF TPT$="3" THEN TX=5.949: TY=7.62: TZ=4.854: GOTO 7150
7080  IF TPT$="4" THEN TX=6.096: TY=8.247: TZ=0: GOTO 7150
7090  IF TPT$="5" THEN TX=1.016: TY=15.867: TZ=.226
7100  IF TPT$="F1" THEN TX=0: TY=0: TZ=0: GOTO 7150  ' FID 1
7110  IF TPT$="F2" THEN TX=-1.671: TY=7.62: TZ=4.854: GOTO 7150  ' FID 2
7120  IF TPT$="F3" THEN TX=1.016: TY=15.867: TZ=-1.75: GOTO 7150 ' FID 3
7130  GOTO 7010
7140 '
7150  GOSUB 5260  ' CALL SLICE TO CALCULATE VALUES
7160 '
7170 ' PRINT FOCAL PLANE COEFFICIENTS
7180 PRINT
7190 PRINT"FOCAL PLANE COEFFICIENTS (A,B,C,D)"
7200 PRINT
7210 PRINT FPLANE(1),FPLANE(2),FPLANE(3),FPLANE(4)
7220 '
7230 PRINT
7240 PRINT "DIRECTION COSINES (X,Y,Z)"
```

```
7250 PRINT
7260 PRINT DCOSX,DCOSY,DCOSZ
7270 PRINT
7280 '
7290 ' PRINT TRUE AND CALCULATED VALUES OF THE FOCAL POINT AND THE ERROR IN MM.
7300 PRINT"FOCAL POINT COORDINATES"
7310  PRINT
7320  PRINT "MEASURED-";FPOINT(1),FPOINT(2),FPOINT(3)
7330  PRINT "     TRUE-";TX,TY,TZ
7340  ER=10*((FPOINT(1)-TX)^2+(FPOINT(2)-TY)^2+(FPOINT(3)-TZ)^2)^.5
7350  PRINT "ERROR IN mm.=";ER
7360  PRINT
7370 '
7380 NEXT TPOINT
7390 '
7400 RETURN
7410 '
7420 ' SUBROUTINE: RECALL-SIT
7430 '
7440 ' THIS SUBROUTINE RECALLS THE COORDINATES OF THE FOCAL, NORMAL AND
7450 ' ORIENTATION POINTS FOR THE "SITTING" SPARK GAP BRACKET FROM THE
7460 ' FILE SIT AND STORES THE COORDINATES IN ARRAY FOCAL(POINT,COORDINATE).
7470 '
7480 OPEN "SIT" FOR INPUT AS #1      ' OPEN FILE "SIT" TO READ IN COORDINATES
7490  FOR PNT=1 TO 3                 ' LOOP THROUGH FOCAL, NORMAL AND ORIENT PT.
7500   FOR COORD=1 TO 3              ' LOOP THROUGH X, Y AND Z COORDINATES
7510    INPUT #1,FOCAL(PNT,COORD)    ' STORE DATA IN ARRAY FOCAL(POINT,COORD)
7520   NEXT COORD                    ' NEXT COORDINATE
7530  NEXT PNT                       ' NEXT POINT
7540 CLOSE #1                        ' CLOSE FILE
7550 RETURN
7560 '
7570 ' SUBROUTINE: RECALL-SUP
7580 '
7590 ' THIS SUBROUTINE RECALLS THE COORDINATES OF THE FOCAL, NORMAL AND
7600 ' ORIENTATION POINTS FOR THE "SUPINE" SPARK GAP BRACKET FROM THE
7610 ' FILE SUP AND STORES THE COORDINATES IN ARRAY FOCAL(POINT,COORDINATE).
7620 '
7630 OPEN "SUP" FOR INPUT AS #1      ' OPEN FILE "SUP" TO READ IN COORDINATES
7640  FOR PNT=1 TO 3                 ' LOOP THROUGH FOCAL, NORMAL AND ORIENT PT.
7650   FOR COORD=1 TO 3              ' LOOP THROUGH X, Y AND Z COORDINATES
7660    INPUT #1,FOCAL(PNT,COORD)    ' STORE DATA IN ARRAY FOCAL(POINT,COORD)
7670   NEXT COORD                    ' NEXT COORDINATE
7680  NEXT PNT                       ' NEXT POINT
7690 CLOSE #1                        ' CLOSE FILE
7700 RETURN
7710 '
7720 ' SUBROUTINE: RECALL-MIKE
7730 '
7740 ' THIS SUBROUTINE RECALLS THE CT COORDINATES OF THE MICROPHONES THAT WERE
7750 ' STORED IN CASE THE COMPUTER FAILED AFTER THE REGISTRATION PROCEDURE.
7760 '
7770 OPEN "MIKE" FOR INPUT AS #1     ' OPEN FILE "MIKE" TO READ IN COORDINATES
7780  FOR MK=1 TO 3                  ' LOOP THROUGH THE MICROPHONES
7790   FOR COORD=1 TO 3              ' LOOP THROUGH X, Y AND Z COORDINATES
7800    INPUT #1,MIKE(MK,COORD)      ' STORE DATA IN ARRAY MIKE(MK,COORD)
7810   NEXT COORD
7820  NEXT MK
7830 CLOSE #1                        ' CLOSE FILE
7840 HFLAG=1                         ' SET RECALL FLAG EQUAL TO 1
7850 RETURN
```

Appendix D - Mechanical Drawings

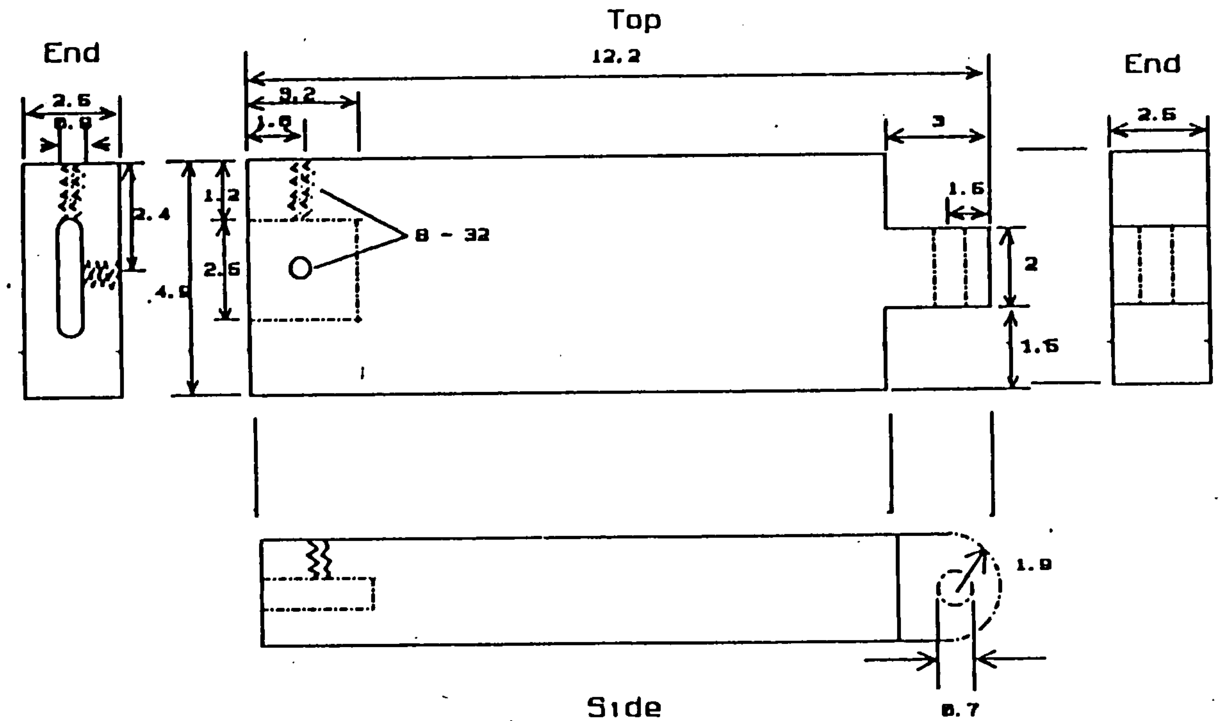
This appendix contains the mechanical drawings for the spark gap holder, spark gap holder brackets, spark gap holder - microscope mount, and the ceiling microphone mounts.


All measurements in cm.
Tapped holes are in inches
Top
Side
8 - 32
1/4 - 28
1.3
4
33
30
25
2.3
5
4.6
3.6
3
2.5
6
1.5
2
3.3
0.8
1.7
1.2
3.5
TITLE: Spark Gap Holder
DATE: 7/13/84
ENGINEER: John F. Hatch
PAGE: D1



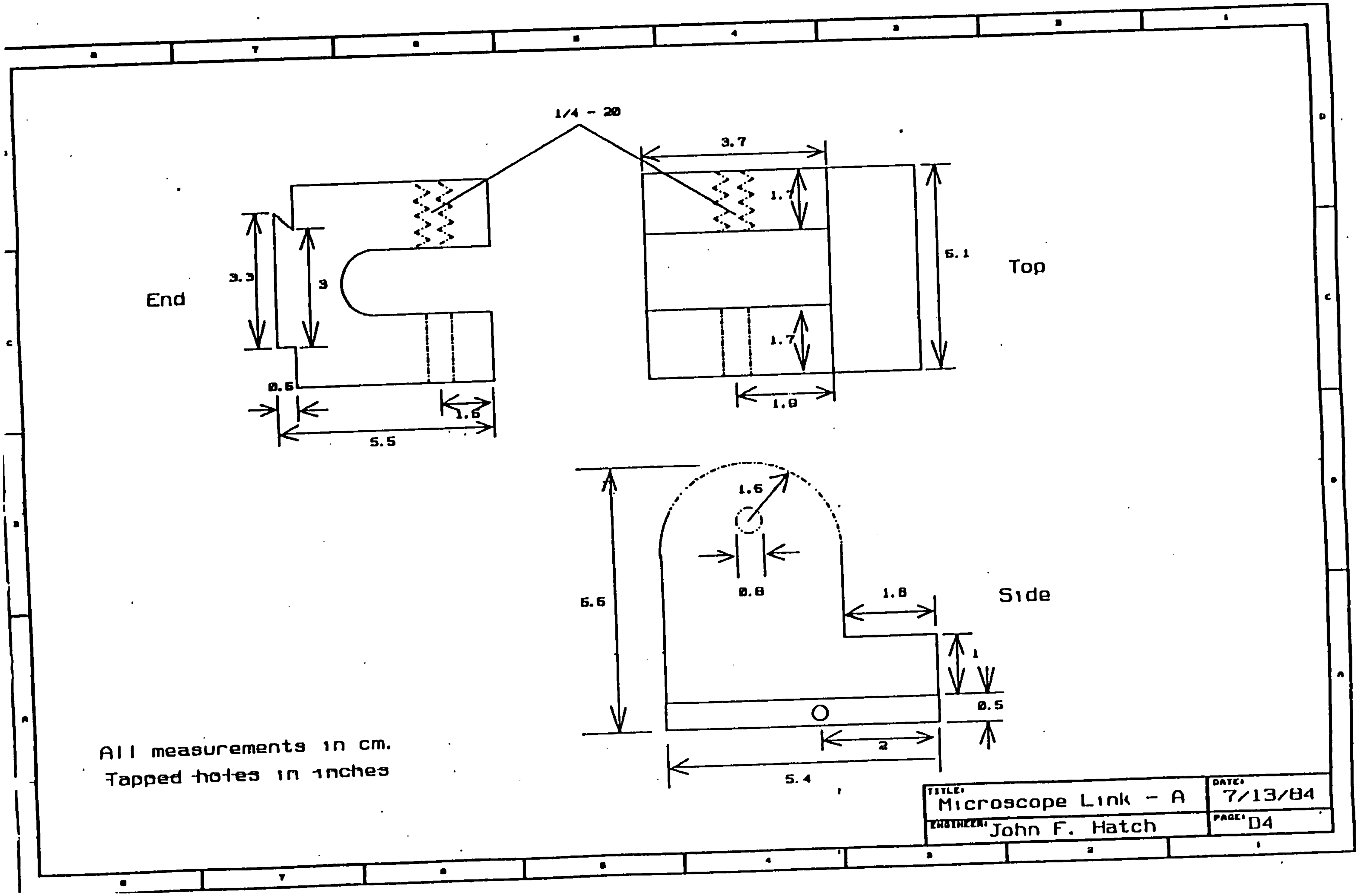
All measurements in cm.
Tapped holes in inches

TITLE: Supine Bracket	DATE: 7/13/84
ENGINEER: John F. Hatch	PAGE: D2



All measurements in cm.
Tapped holes in inches

TITLE: Sitting Bracket	DATE: 7/13/84
ENGINEER: John F. Hatch	PAGE: D3



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End
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3
0.6
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5.5
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Top
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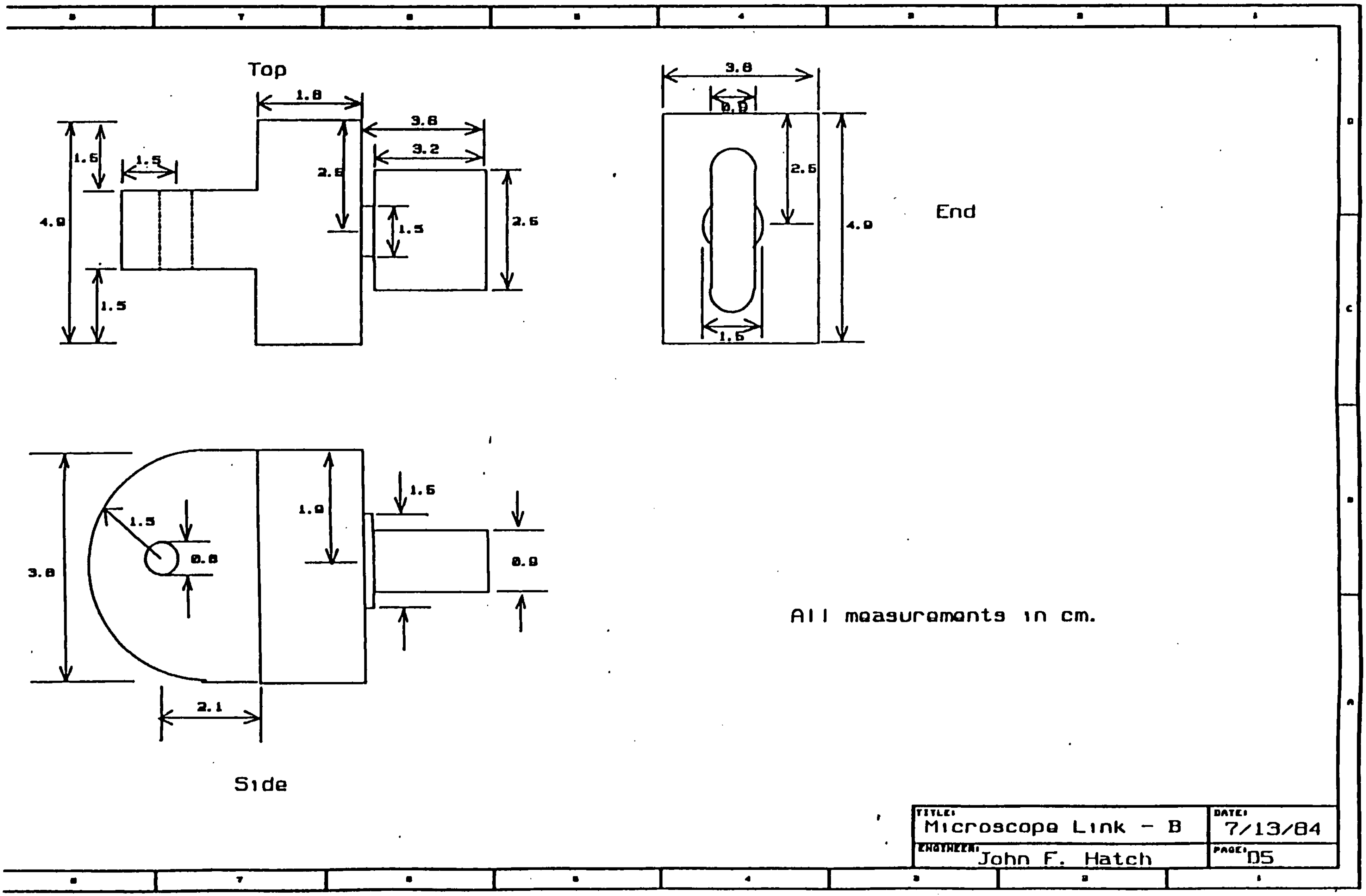
Side
1
0.5
2
5.4
All measurements in cm.
Tapped holes in inches
TITLE: Microscope Link - A
DATE: 7/13/84
ENGINEER: John F. Hatch
PAGE: D4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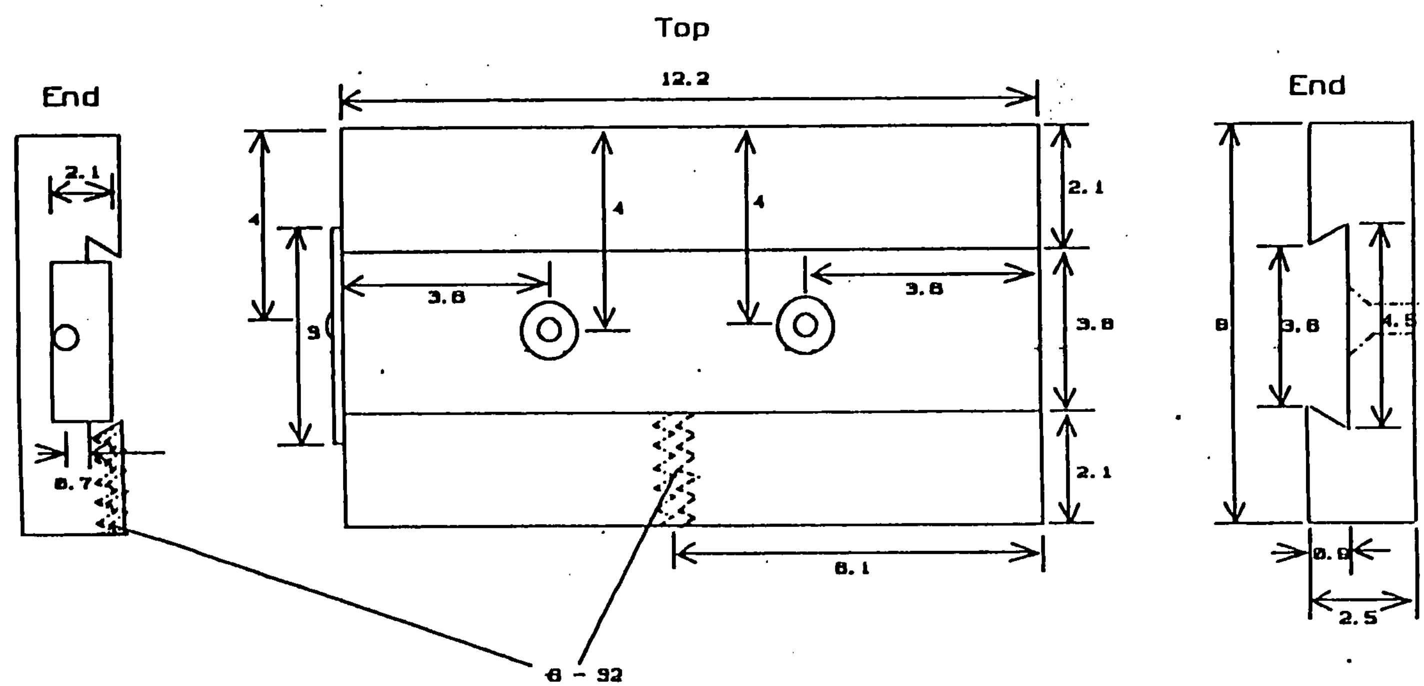
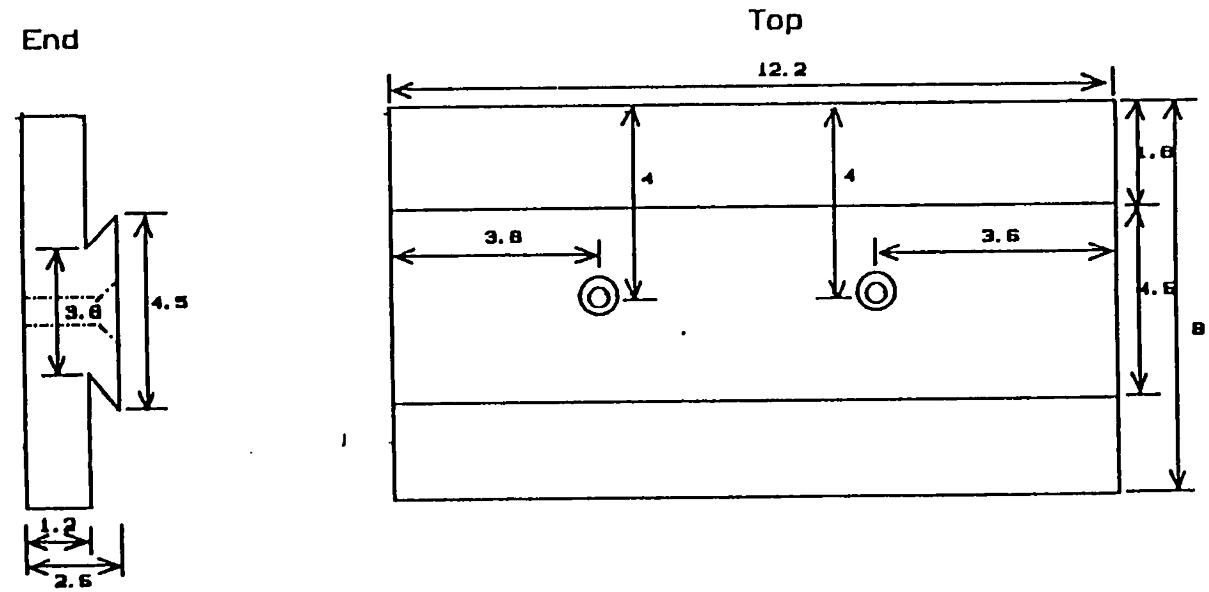
2.6
4.9
1.6
End
1.6
1.5
1.9
0.8
3.8
0.9
2.1
Side
All measurements in cm.
TITLE: Microscope Link - B
DATE: 7/13/84
ENGINEER: John F. Hatch
PAGE: D5



All measurements in cm.
Tapped holes in inches

TITLE: Microphone Mount - A	DATE: 7/13/84
ENGINEER: John F. Hatch	PAGE: D6



All measurements in cm.

TITLE: Microphone Mount - B	DATE: 7/13/84
ENGINEER: John F. Hatch	PAGE: D7

Appendix E - Digitizer Error Statistics

Listed below are the results of the digitizer evaluation. It was determined that the digitizer meets its specifications for precision and that the observed errors in accuracy are most likely due to measurement errors in determining the correct slant range distance, and not due to digitizer error. All values are in centimeters where d is the slant range distance, n is the sample number and sd is the standard deviation.

	d	n	Mean	sd	High Value	Low Value	Range
Theoretical	50	50	50.000		50.01	49.99	0.02
Experimental		50	49.889	0.0027	49.89	49.88	0.01
		100	49.891	0.0059	49.90	49.88	0.02
		150	49.900	0.0028	49.91	49.89	0.02
Theoretical	100	50	100.00		100.01	99.99	0.02
Experimental		50	99.904	0.0069	99.91	99.89	0.02
		100	99.915	0.0058	99.93	99.90	0.02
		150	99.929	0.0071	99.92	99.90	0.02
Theoretical	150	50	150.00		150.01	149.99	0.02
Experimental		50	149.63	0.0038	149.64	149.62	0.02
		100	149.65	0.0067	149.66	149.62	0.02
		150	149.68	0.0048	149.69	149.62	0.02
Theoretical	200	50	200.00		200.01	199.99	0.02
Experimental		50	199.30	0.0061	199.30	199.28	0.02
		100	199.32	0.0045	199.33	199.31	0.02
		150	199.33	0.0068	199.34	199.32	0.02

Appendix F - Experimental Data

This Appendix is divided into four sections, focal point accuracy and precision, resting focal point precision, focal plane accuracy and spark gap holder precision. The experimental criteria is explained with each section.

Focal Point Accuracy

This purpose of this experiment was to determine the reference system accuracy and precision at the focal point. First the test phantom coordinates of the microphones were determined by focusing on each of the three test fiducials. Then the microscope was focused at ten different angles on four test points whose coordinates are known in the test coordinate system. The table below shows the magnitude of the focal point errors in millimeters for each sample, n, and the mean and standard deviations (sd) for each test point.

	Test Point #			
n	1	2	3	4
1	0.79	1.76	2.47	0.99
2	0.58	0.53	1.22	1.28
3	1.45	1.33	0.97	0.74
4	0.18	1.98	0.57	1.57
5	0.67	0.66	0.86	1.06
6	0.49	0.45	1.29	1.59
7	1.00	0.48	0.38	1.60
8	0.57	0.58	0.48	0.72
9	1.10	1.43	1.73	2.28
10	0.83	0.86	0.91	2.17

Mean	0.77	1.01	1.09	1.40
sd	0.356	0.566	0.634	0.545
Average Mean	1.07			
Average sd	0.526			

Resting Focal Point Precision

The purpose of this experiment was to determine the reference system precision at the focal point, in other words, how much do the coordinates of the focal point vary without refocusing the microscope between samples. After registering the microphones, the microscope was focused on one test point and fifteen samples taken. The standard deviations were then calculated to give an estimate of the variations that could be expected during a typical case due to variable air motions, etc. Each spark gap was fired 30 times. The number of samples is n, the coordinates are in centimeters, and the standard deviation is sd.

	Coordinates		
n	X	Y	Z
1	-4.65	7.76	0.73
2	-4.70	7.64	0.69
3	-4.67	7.76	0.72
4	-4.63	7.75	0.72
5	-4.64	7.69	0.68
6	-4.53	7.77	0.61
7	-4.60	7.80	0.69
8	-4.65	7.70	0.72
9	-4.66	7.75	0.73
10	-4.62	7.74	0.69
11	-4.67	7.78	0.76
12	-4.63	7.71	0.72
13	-4.65	7.63	0.68
14	-4.69	7.74	0.76
15	-4.56	7.65	0.62

Mean	-4.64	7.72	0.70
sd	0.057	0.066	0.055

Focal Plane Accuracy

The purpose of this experiment was to determine the accuracy of the focal plane calculations. Since the focal plane is defined by four coefficients in the form Ax + By + Cz = D, it is difficult to determine the plane accuracy. Therefore, the microscope was focused on the grid coordinate system (Figure 9.1) normal to the z axis where the equation of the plane is z=0, and the plane coefficients determined. Ideally, A, B and D should equal 0 and C equal 1.

The accuracy of the focal plane orientation was determined by calculating the x and y axis direction cosines of the focal point - orientation point vector in the first quadrant of the grid coordinate system. The sum of these angles should be theoretically 90°.

The focal plane coefficients and sum of direction cosine angles in degrees are indicated below for fifteen refocused samples (n), along with the means and standard deviations (sd).

Focal Plane Coefficients

n	A	B	C	D	Angle
1	-.044	.101	1	-.042	84.3
2	-.037	.108	1	.053	90.8
3	-.025	.090	1	-.060	84.6
4	-.027	.118	1	-.015	91.4
5	-.030	.121	1	-.053	91.0

6	-.035	.091	1	-.015	91.2
7	-.031	.118	1	.064	91.2
8	-.029	.109	1	.021	92.8
9	-.040	.100	1	.037	90.7
10	-.041	.900	1	.017	91.9
11	-.041	.102	1	-.112	91.0
12	-.031	.101	1	.017	90.7
13	-.027	.105	1	.019	95.7
14	-.022	.118	1	.035	92.6
15	-.021	.119	1	.018	92.6
Mean	-.0321	.1061		.0053	90.33
sd	.0072	.0110		.0503	2.89

Spark Gap Holder Precision

The purpose of this experiment was to quantitatively determine the error due to repositioning the spark gap holder between oblique focal, normal and orientation point determination and the actual procedure. The focal point coordinates (in cm.) were determined fifteen times without refocusing the microscope on the spark gap 4 and the average values were -3.509 (x), -3.723 (y) and -39.371 (z) with standard deviations of 0.035 (x), 0.035 (y) and 0.022 (z). The spark gap holder was then removed and the sterile drape bag placed over the microscope. The spark gap holder was replaced after the drape bag was stretched over the metal tongue of the microscope mount. The focal point coordinates (in cm.) were determined fifteen times after the microscope was refocused on spark gap 4 and the average values were -3.430 (x), -3.783 (y) and -39.391 (z) with standard deviations of 0.058 (x), 0.053 (y) and 0.025 (z). The

magnitude of error is the square root of the sum of the squares of the differences in x, y and z.

$$|\vec{e}_{s\text{-}holder}| = \sqrt{0.0063^2 + 0.0030^2 + 0.0004^2}$$

$$|\vec{e}_{s\text{-}holder}| = 0.9 \text{ millimeters.}$$

This error might be reduced by designing a better spark gap holder - microscope mount once the limitations and physical constraints of the operating room have been experimentally determined.

Appendix G - Digitizer Operator's Manual

This appendix is a step by step guide to the setup and operating procedure for the reference-display system. The relationship between the spark gaps and the focal, normal and orientation points must be determined first by running file FPL and following the instructions given. Below is a description of the procedure in the operating room.

Display System

1. Place the microscope in an upright position.

2. Remove the ocular assembly and camera-observer beam splitting assembly.

3. Attach the display assembly, with the projection tube to the left (See Figure 3.5), to the microscope.

4. Replace the camera-observer beam splitting assembly and the ocular assembly.

5. Connect the +12 volt d-c power supply and the composite video input cable (from the Interact TV patch panel on the operating room ceiling) to the display assembly.

Spark Gaps

6. Attach the microscope-spark gap link (unsterile) to the laser mount on the microscope, securing the set screw.

7. Place a sterile drape bag over the microscope.

8. Pull the sterile drape over the "tongue" of the microscope-spark gap link until a hole is made in the drape bag. (Note: be careful not to touch the unsterile "tongue", cutting the hole partially open will help.)

9. Attach the sterile spark gap holder to the microscope-spark gap link and tighten the set screws into the recessions on the "tongue".

10. Attach the spark gaps to the spark gap holder, tightening each set screw.

11. Balance the microscope.

Digitizer - Computer System

12. Attach the four microphones to the microphone mounts on the operating room ceiling.

13. Connect the ribbon microphone cable from the microphones to the DB-25 connector on the front panel of the digitizer.

14. Connect the three spark gaps to the front panel of the spark gap multiplexer.

15. Connect the hex connector spark gap input from the back panel of the multiplexer to the front panel of the digitizer.

16. Connect the digitizer output (back panel-terminal port) to the RS-232 serial port on the back of the IBM PC XT, via the DB-25 connector ribbon cable.

17. Attach the parallel port of the IBM to the back panel of the multiplexer.

18. Set the multiplexer to computer mode.

19. Turn on the IBM with a system disk in drive A. The screen will ask for you to enter the date and time which can be ignored by pressing "RETURN".

20. On the back panel of the digitizer, make sure the foot pedal plug (without cable) is in place and the "terminal" switch is on. On the front panel, make sure that the toggle switch is on "line" and the rate knob turned completely clockwise (maximum).

21. Type "C:" in response to the prompt "A>" and then type "FPL" for the focal plane determination, or "REG" for the surgical procedure.

22. Follow the directions of the software for the rest of the procedure.

Note: It is best to test the registration system (File REG) after determining the spark gap - focal plane relationship (File FPL) to see if the error at the test points is approximately one millimeter.

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